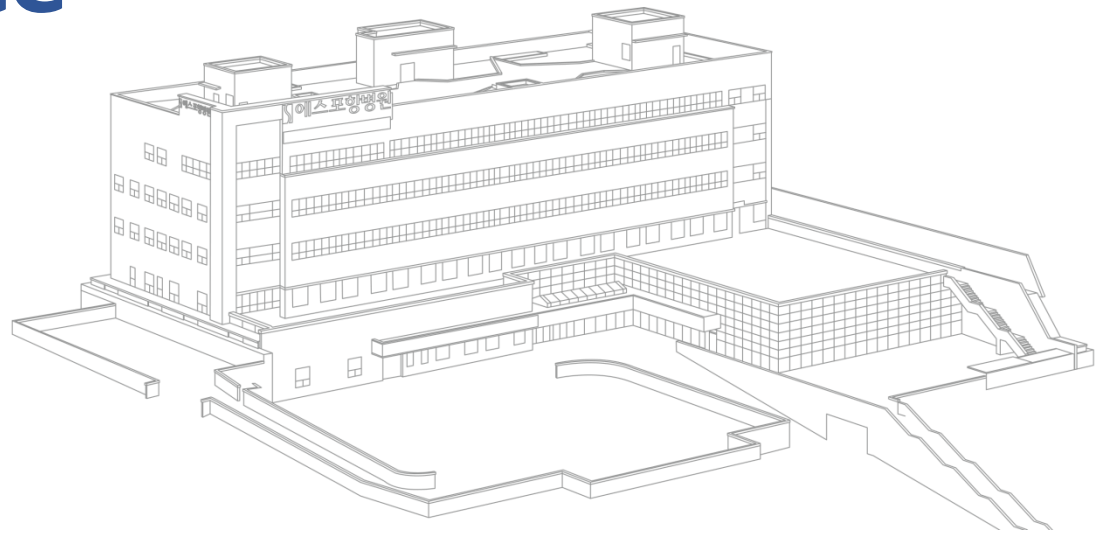
IONM Setting and Practice in Spine Surgery



에스포항병원 재활의학과
이상억

에스포항병원
POHANG STROKE AND SPINE HOSPITAL

IONM in Spine Surgery

- **Early 1970s**
  - Epidural recordings of spinal potentials evoked by direct spinal simulation
- **Mid-1970s**
  - Spinal IONM using **somatosensory evoked potentials (SEPs)**
    - Middle- & Long-latency 50 – 200 ms cortical potentials during orthopedic procedure
- **Early 1990s**
  - **Transcranial electrical stimulation** as a practical corticospinal technique under anesthesia
- 1981
  - **Commercial IONM equipment**

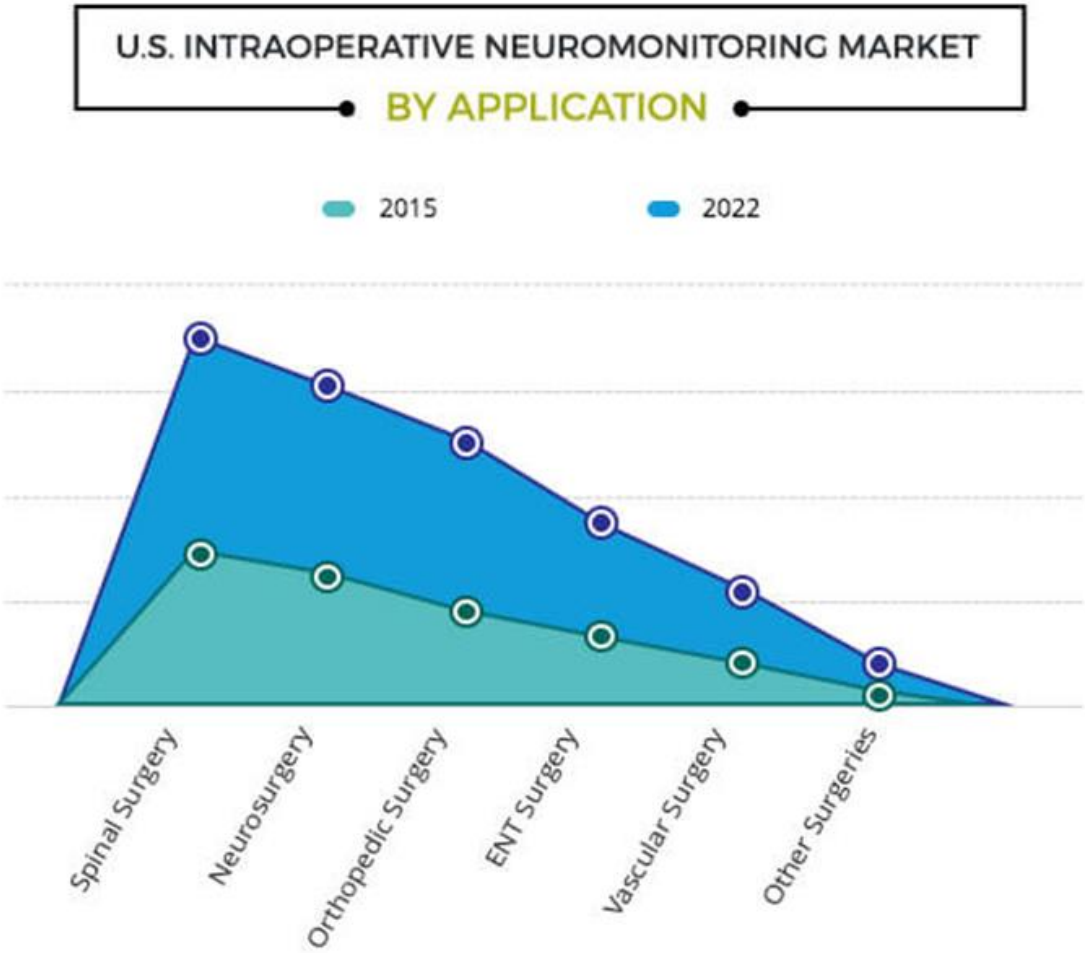
Type of surgery in IONM

Type of surgery	Percentage
Carotid	13.5
Intracranial aneurysms, AVM	3.2
Intracranial tumors	6.2
Epilepsy resections	6.4
Movement disorders	9.4
Intracranial CN decompression, CPA tumors	3.8
Cervical spine	19.1
Thoracic spine	8.8
Aorta, cardiac	0.9
Lumbar discectomy, fusion	20.5
Tethered cord, rhizotomy	2.6
Peripheral nerve, plexus, arm, leg	2.5
Middle ear, mastoid, parotid, thyroid	2.1
Other	1.2

Abbreviations: AVM = arterial venous malformation; CN = cranial nerve; CPA = cerebello-pontine angle.

(Nuwer, Cohen, & Shepard, 2013)

Type of surgery in IONM



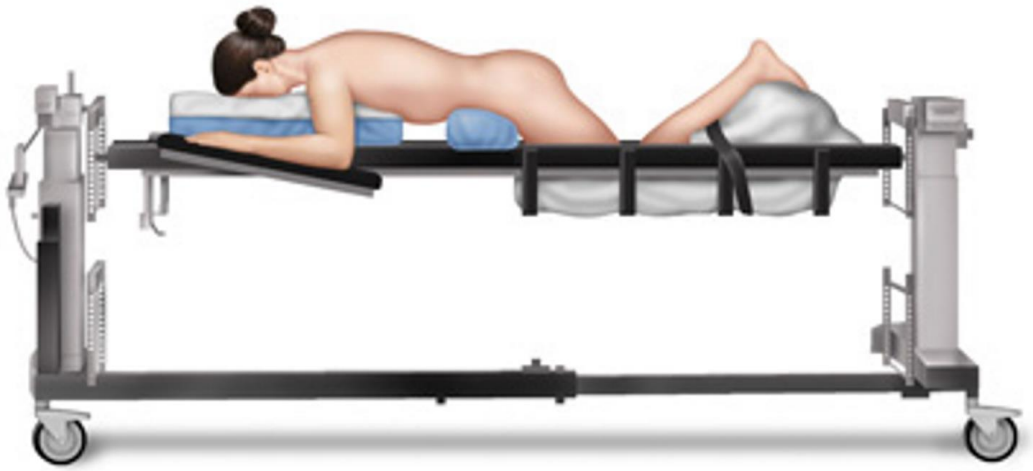
SPINAL SURGERY holds a dominant position in 2015 and would continue to maintain the lead over the forecast period.

Indication

급여기준

- 척수증(Myelopathy) 가 있는 경우
- 측만증, 후만증 등의 기형 (Deformity) 가 있는 경우
- 척수의 선천성 또는 종괴성 병변 (척수종양, 척수공동증, 혈관기형, 당김척수증후군 (Tethered cord syndrome) 등이 있는 경우
- 두개저 경추 연접부위, 상부 경추 척추 불안정이 있는 경우

Risk in spine surgery

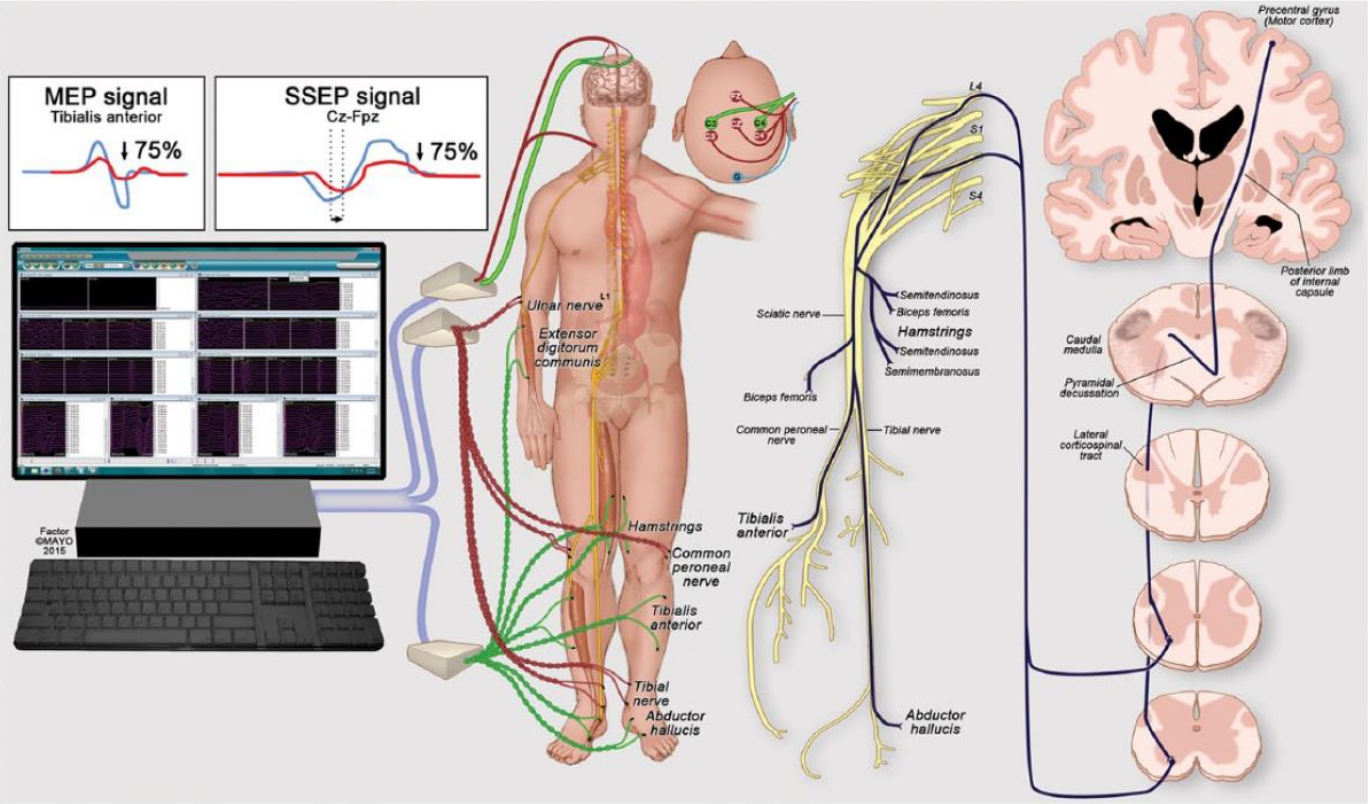


- Risk
  - **Spinal cord**
  - **Nerve root**
  - Brachial plexus
  - Peripheral nerve
- major neurologic complication
  - Incidence: **About 1%**

(MacDonald, Al-Enazi, & Al-Zayed, 2008)

(Nuwer & Schrader, 2019)

Injury mechanism in spine surgery



Ischemia

Compression

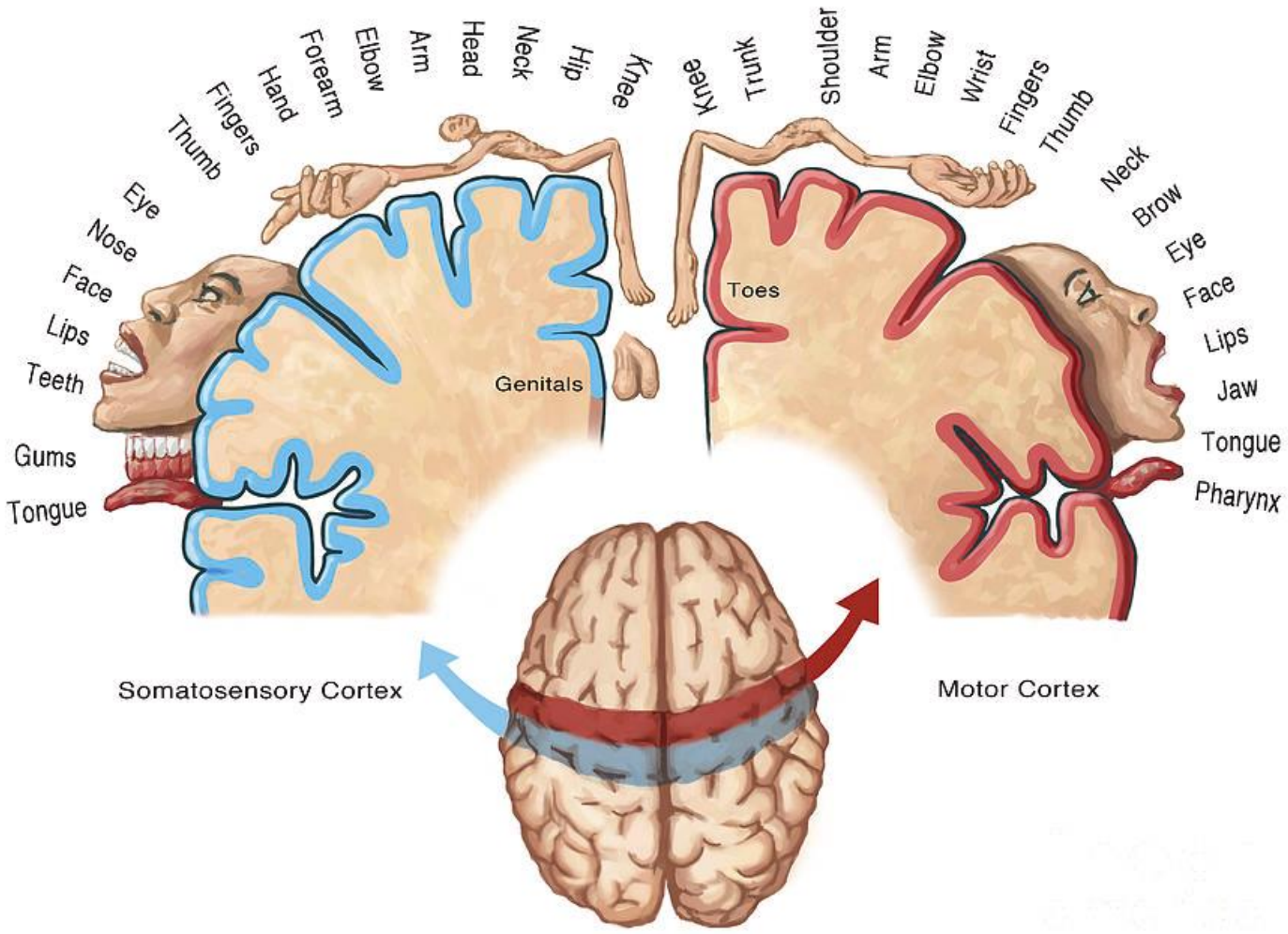
Traction

(MacDonald, Al-Enazi, & Al-Zayed, 2008)

IONM modalities in spine surgery

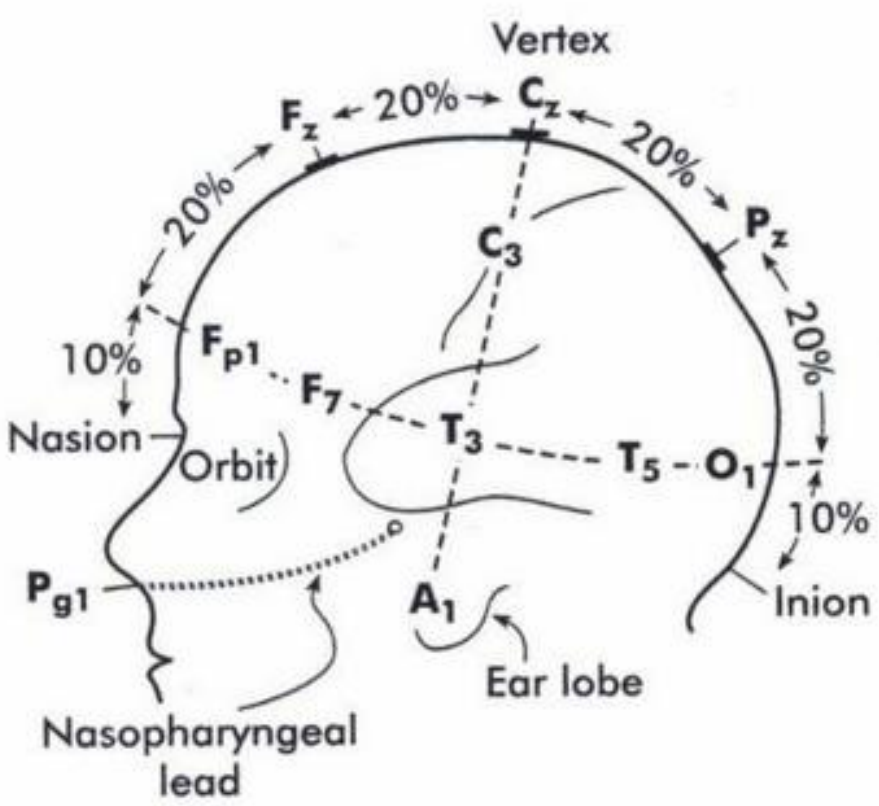
- Somatosensory Evoked Potential
- Transcranial Motor Evoked Potential
- Electromyography
- Others

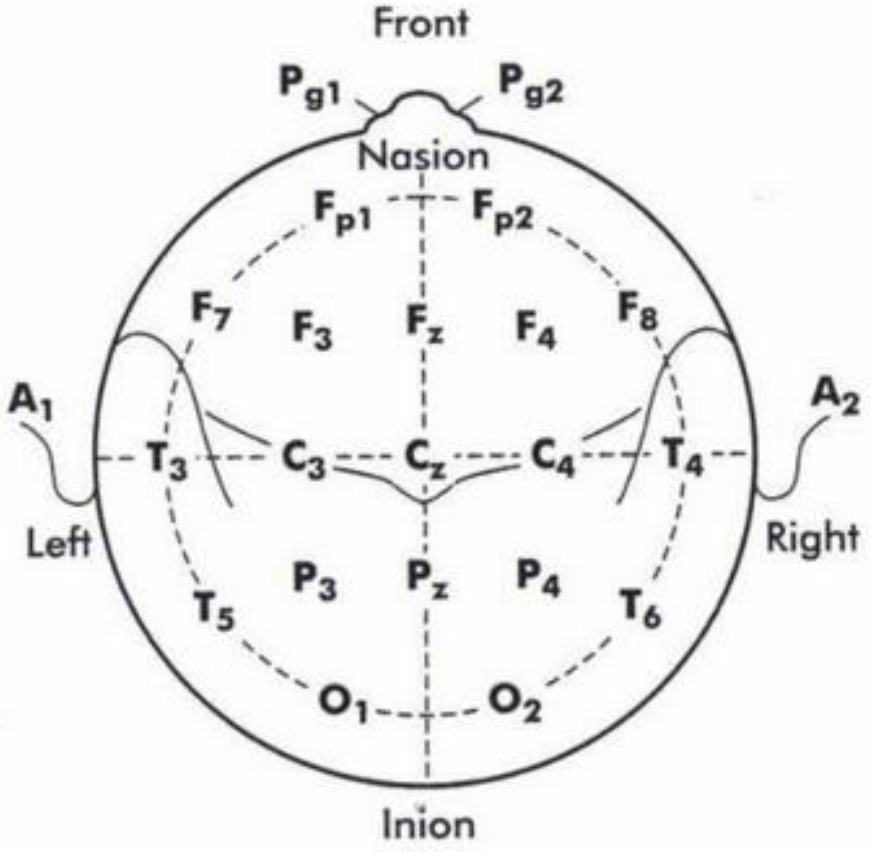
Electrical Potential - Montage



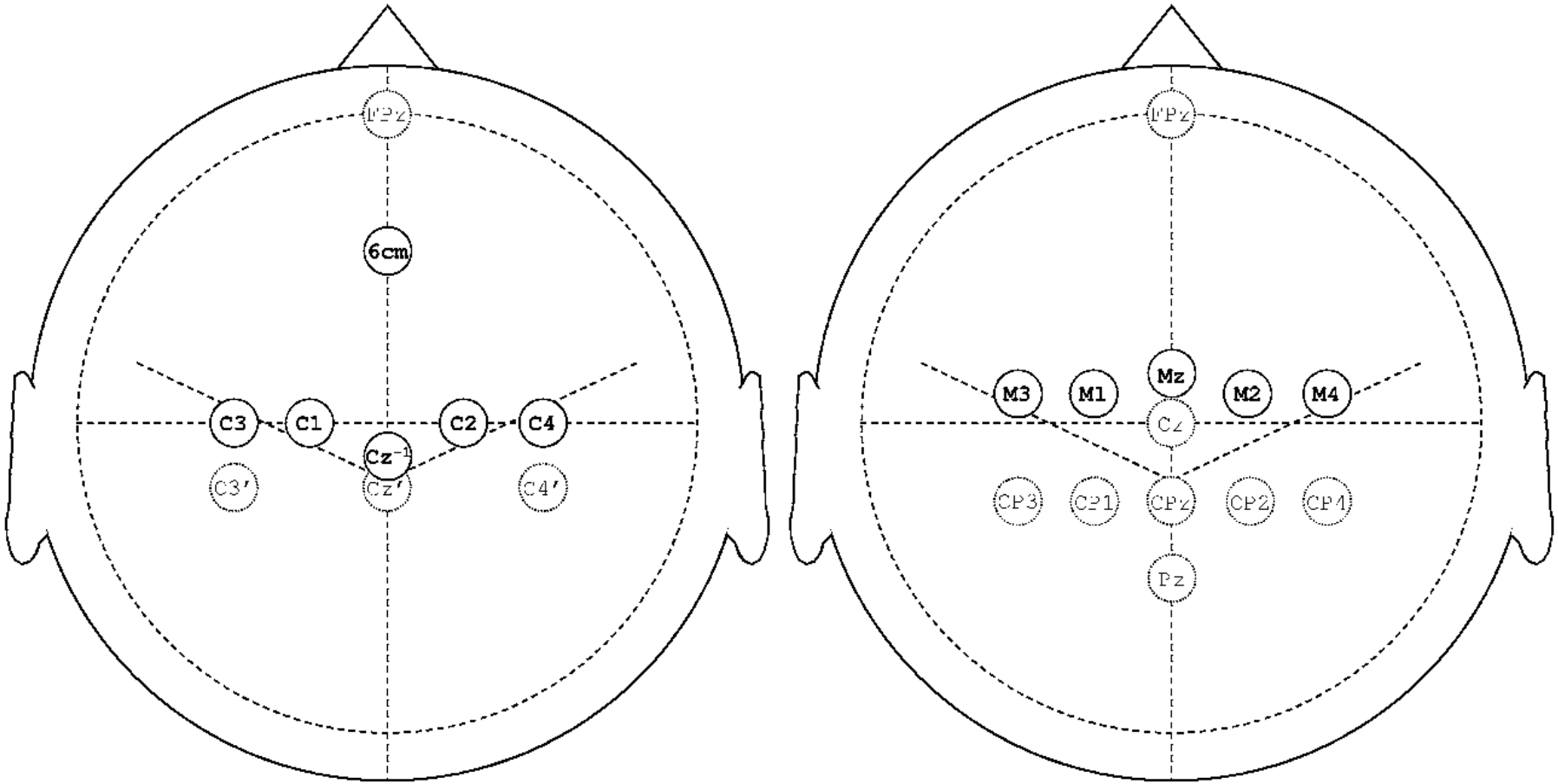
Electrical Potential - Montage

10-20 system - electrodes positioning





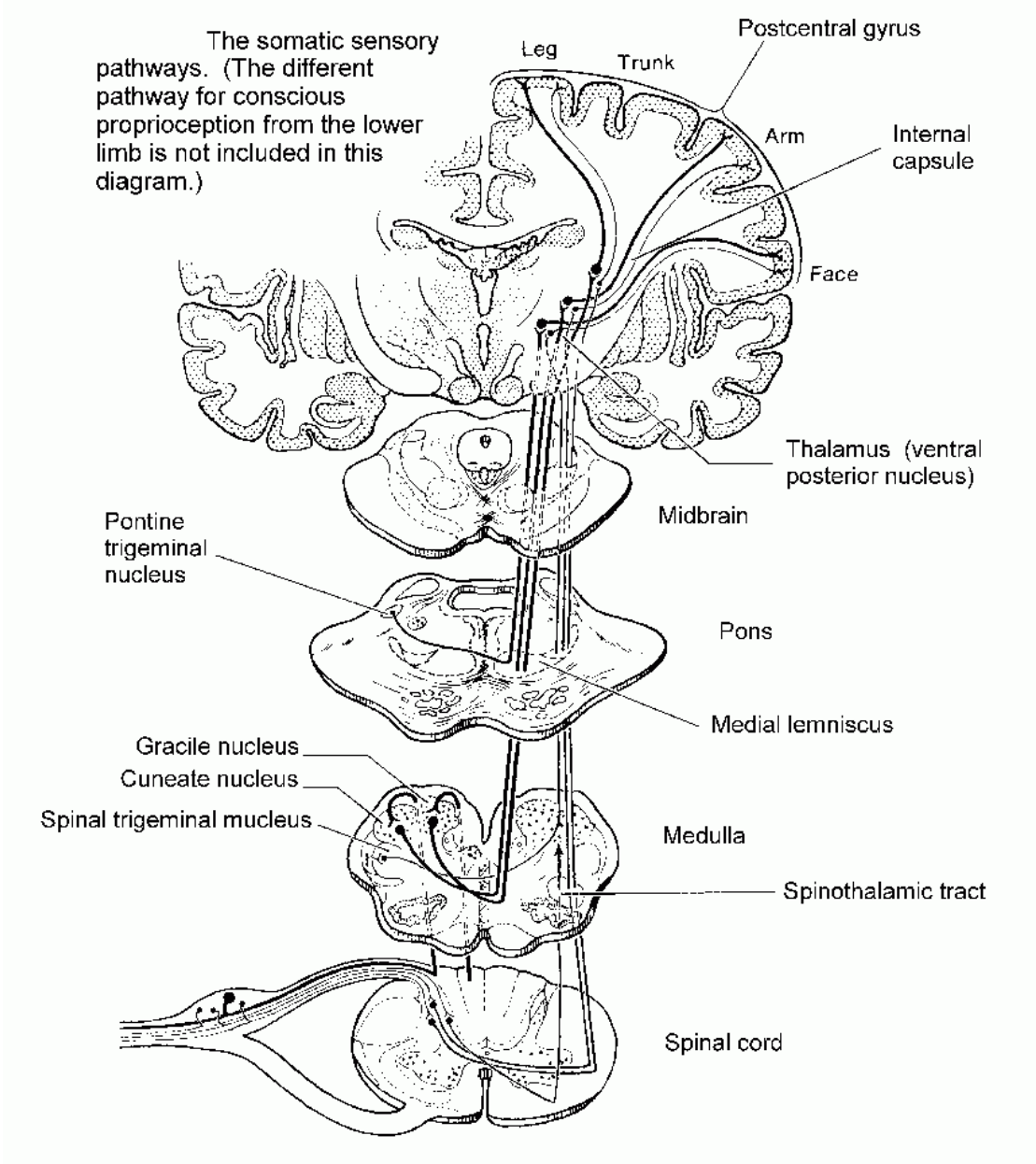
Electrical Potential - Montage



SEP

- Spinothalamic tract
- **Spinal Dorsal Column**

- Upper extremity
  - Median (or Ulnar) nerve
- Lower extremity
  - Posterior tibial (or Peroneal)nerve

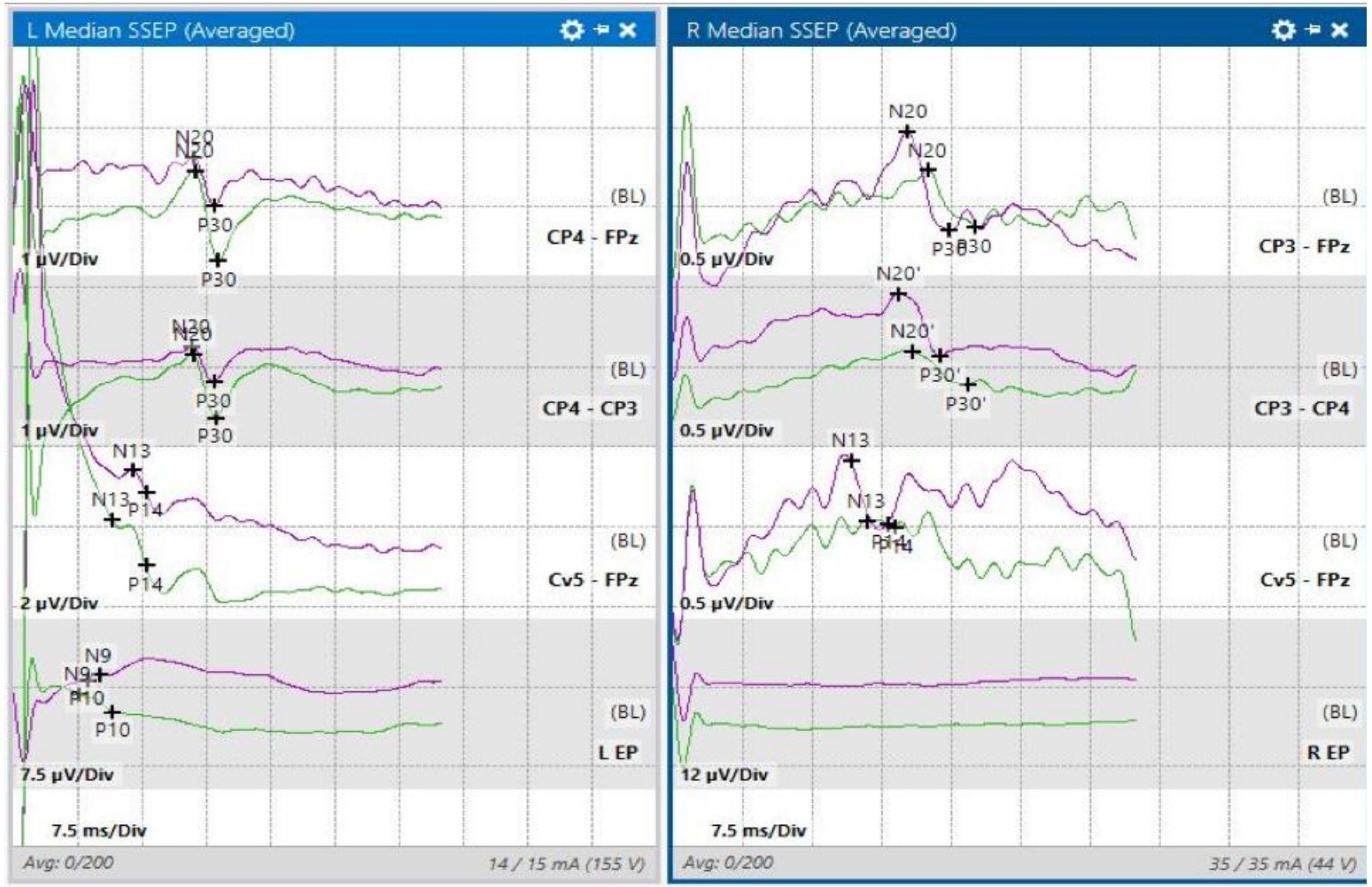


SEP stimulation & recording parameters

	Median nerve	Tibial nerve
Pulse width	300 (200–500) μs	300 (200–500) μs
Intensity	max. 20–25 mA	max. 25–30 mA
Stimulation rate	5.3 Hz	5.3 Hz
Recording sites	C3′, C4′ (C5) vs Fpz	Cz (lower cervical) vs Fpz
Sweep length	50 ms post stim	100 ms post stim
Averages	150–250	150–250
Band pass	30–3000 (500) Hz	30–3000 (500) Hz

(Deletis & Shilis, 2002)

SEP



Scalp **Cortical function**

Scalp **Cortical function**

C5s **Brainstem**

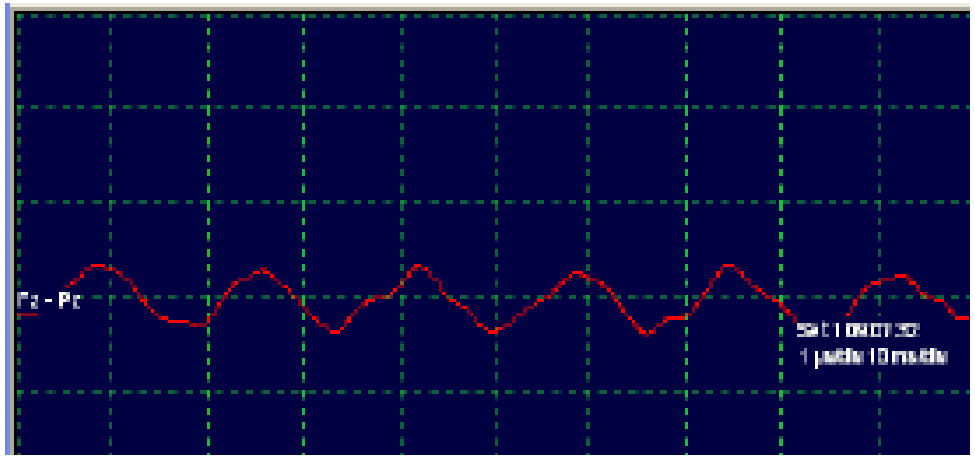
Erb's **Brachial Plexus**

Alarm or Alert for SEP changes

	Amplitude reduction	Latency increase	Reproducibility
Breitner and Matzen, 1985	Instability or loss of SEP	N/A	N/A
Brown and Nash, 1985	>50%	>3 ms	Persistent change over 15 minutes
Koht *et al.*, 1985	≥50%	≥10%	Over two successive recordings
Young and Berenstein, 1985	>Baseline variation	N/A	Over three recordings or 5 minutes
Nuwer, 1986	50%	N/A	N/A
Dawson *et al.*, 1991	50%	10%	N/A
Nuwer, 1999	50%	>5%	N/A
Seyal and Mull, 2002	>50%	>5–10%	N/A
MacDonald *et al.*, 2003	"amplitude alteration occurring abruptly or as a trend"	N/A	"clearly exceeding trial-to-trial variability"
Chen *et al.*, 2004	50%	10%	Compared with baseline recordings obtained after anesthesia induction
Schwartz *et al.*, 2007	> or equal to	Specifically not used to issue an alert	N/A
Strommen, 2009	50%	5%	N/A

Aliasing SEP

- Most common noise frequency
  - **60 Hz**



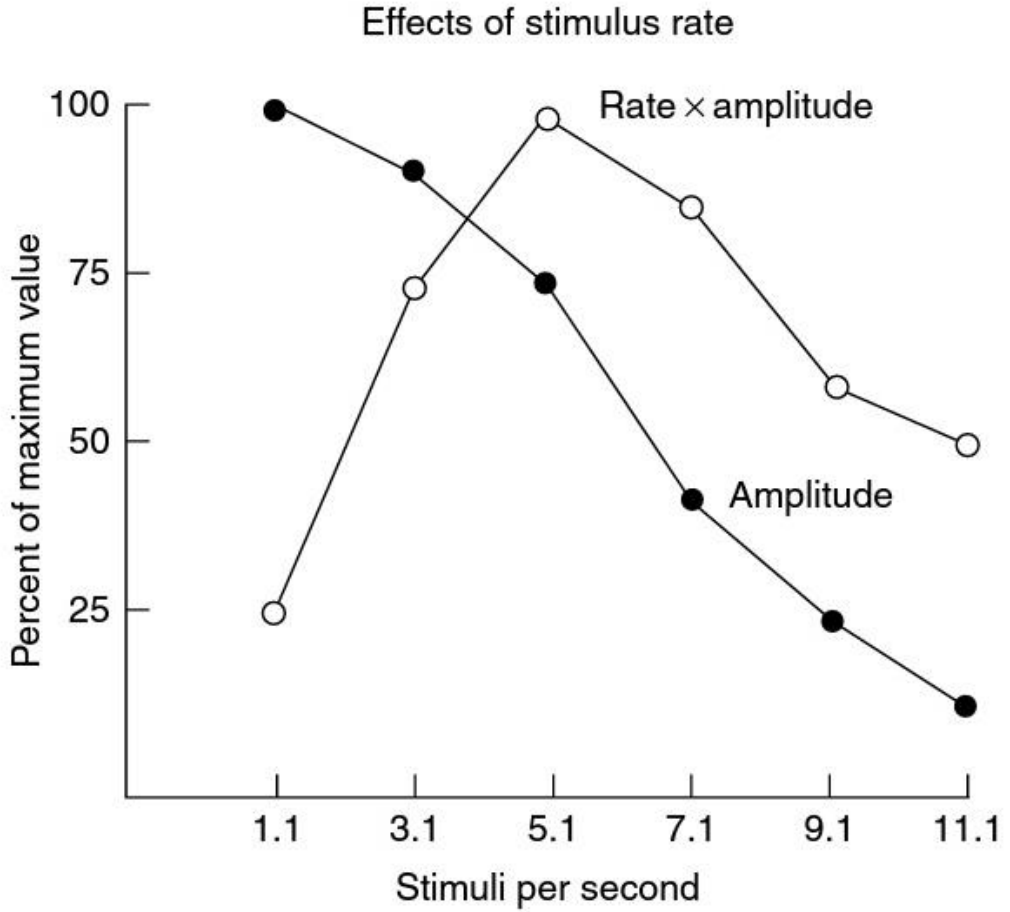


Figure 6.1 Effects of increasing stimulus rate for lower extremity SEPs. As the rate increases, the EP amplitude decreases. The product of rate and amplitude shows the trade-off between advantageous increase in speed of testing and disadvantageous loss of amplitude. In this case, 5.1 per second appeared to be the best compromise between speed and attenuation (from Nuwer and Dawson, 1984a, with permission).

	Noise Frequency												
Rep Rate	**60**	**120**	**180**	**240**	**300**	**360**	**420**	**480**	**150**	**330**	**2500**	**2800**	**3000**
33.27	1.803	3.607	5.410	7.214	9.017	10.821	12.624	14.427	4.509	9.919	75.143	84.160	90.171
33.28	1.803	3.606	5.409	7.212	9.014	10.817	12.620	14.423	4.507	9.916	75.120	84.135	90.144
33.29	1.802	3.605	5.407	7.209	9.012	10.814	12.616	14.419	4.506	9.913	75.098	84.109	90.117
33.30	1.802	3.604	5.405	7.207	9.009	10.811	12.613	14.414	4.505	9.910	75.075	84.084	90.090
33.31	1.801	3.603	5.404	7.205	9.006	10.808	12.609	14.410	4.503	9.907	75.053	84.059	90.063
33.32	1.801	3.601	5.402	7.203	9.004	10.804	12.605	14.406	4.502	9.904	75.030	84.034	90.036
33.33	1.800	3.600	5.401	7.201	9.001	10.801	12.601	14.401	4.500	9.901	75.008	84.008	90.009
33.34	1.800	3.599	5.399	7.199	8.998	10.798	12.597	14.397	4.499	9.898	74.985	83.983	89.982
33.35	1.799	3.598	5.397	7.196	8.996	10.795	12.594	14.393	4.498	9.895	74.963	83.958	89.955
33.36	1.799	3.597	5.396	7.194	8.993	10.791	12.590	14.388	4.496	9.892	74.940	83.933	89.928
33.37	1.798	3.596	5.394	7.192	8.990	10.788	12.586	14.384	4.495	9.889	74.918	83.908	89.901
33.38	1.797	3.595	5.392	7.190	8.987	10.785	12.582	14.380	4.494	9.886	74.895	83.883	89.874
33.39	1.797	3.594	5.391	7.188	8.985	10.782	12.579	14.376	4.492	9.883	74.873	83.857	89.847

Frequency of Noise / Rep Rate = Whole # + 0.5

Ok if between 0.25 - 0.75 but best if closer to 0.5.

	Noise Frequency												
	60	**120**	**180**	**240**	**300**	**360**	**420**	**480**	**150**	**330**	**2500**	**2800**	**3000**
P-P (msec)	16.66	8.33	5.55	4.16	3.33	2.77	2.38	2.08	6.66	3.03	0.4	0.35	0.33

To determine the frequency of the noise:

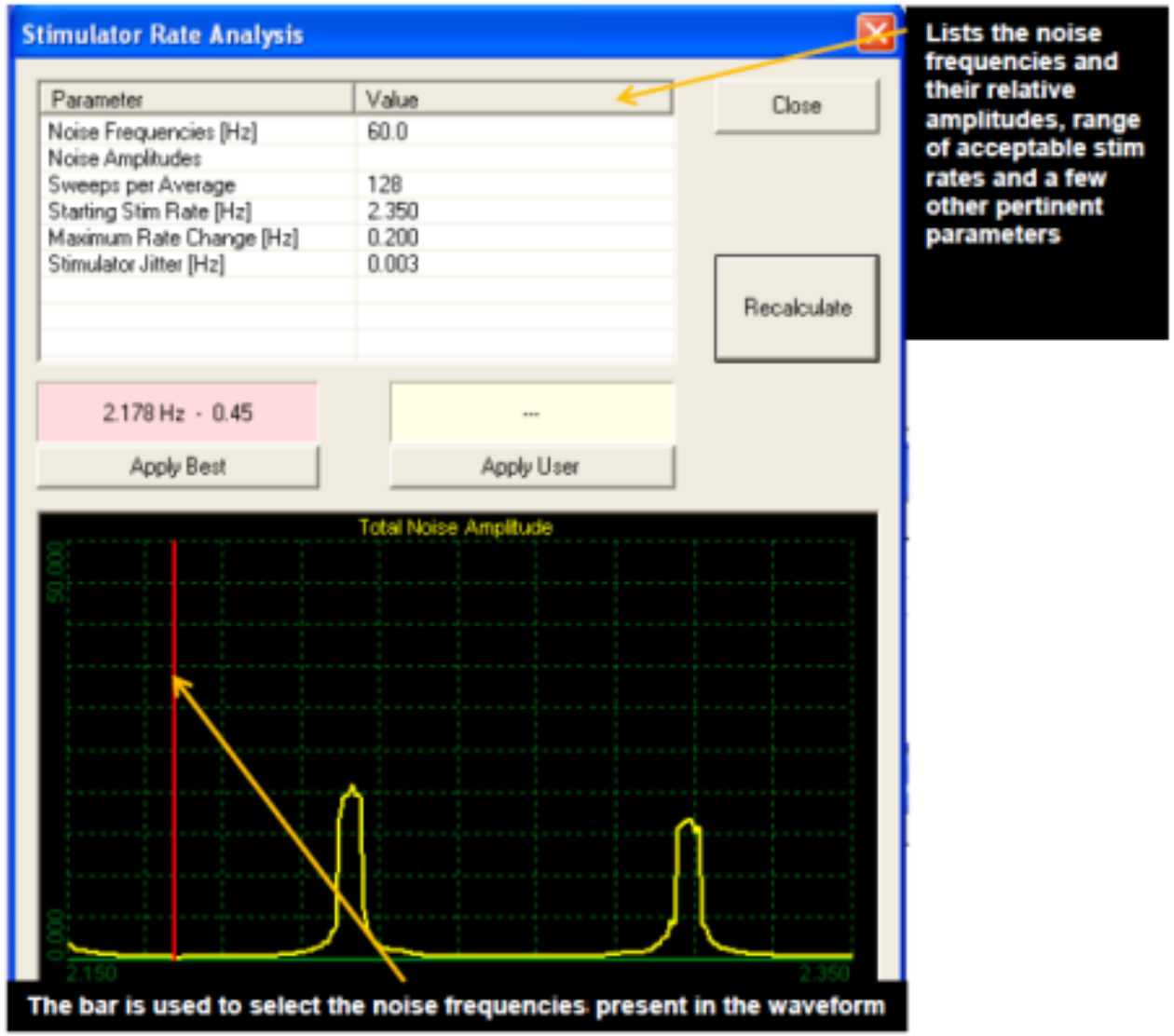
Measure the Peak to Peak interval (msec) of the noise from the LIVE trace in the EP Average window.

Automatic Stimulation Rate Adjustment

Automatically adjusts stimulation rate in accordance to the known frequencies.

Manage Stimulator Settings

Allows user to manually find optimal stimulation rates given their choice of noise frequencies.



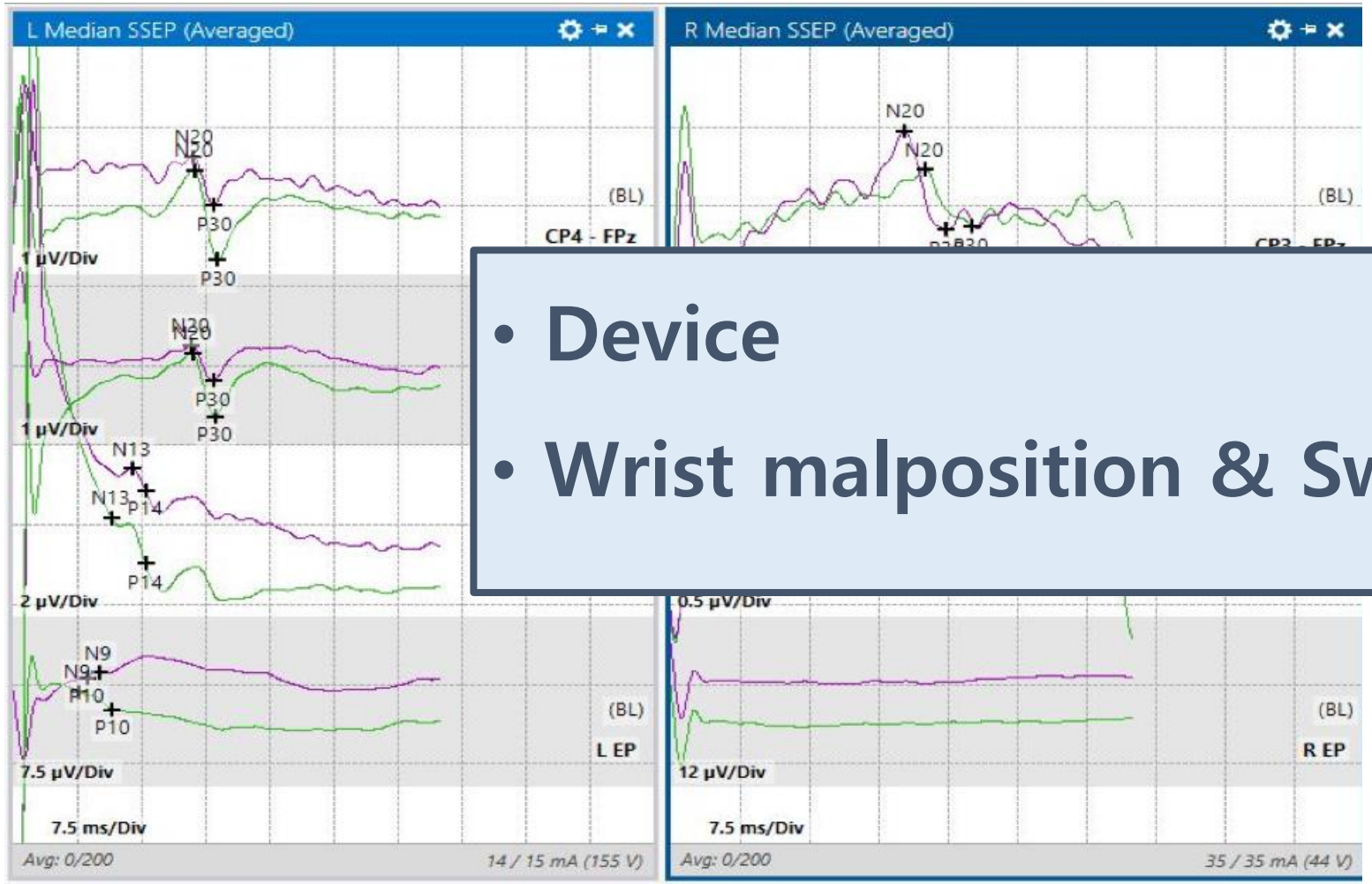
SEP

TABLE 2.5 Localization of Neural Dysfunction Based on Pattern of SEP Changes*

Locus of neural insult	Associated pattern of SEP degradation
Spinal cord dysfunction	Loss of subcorticaland cortical signals, Erb's point intact
Limb malpositioning	Unilateral loss of Erb's point, subcortical and cortical signals
Cerebral ischemia (carotid retraction)	Unilateral cortical loss, intact subcortical signal
Anesthetic effect	Global cortical loss, intact subcortical signals

(Husain, 2008)

SEP



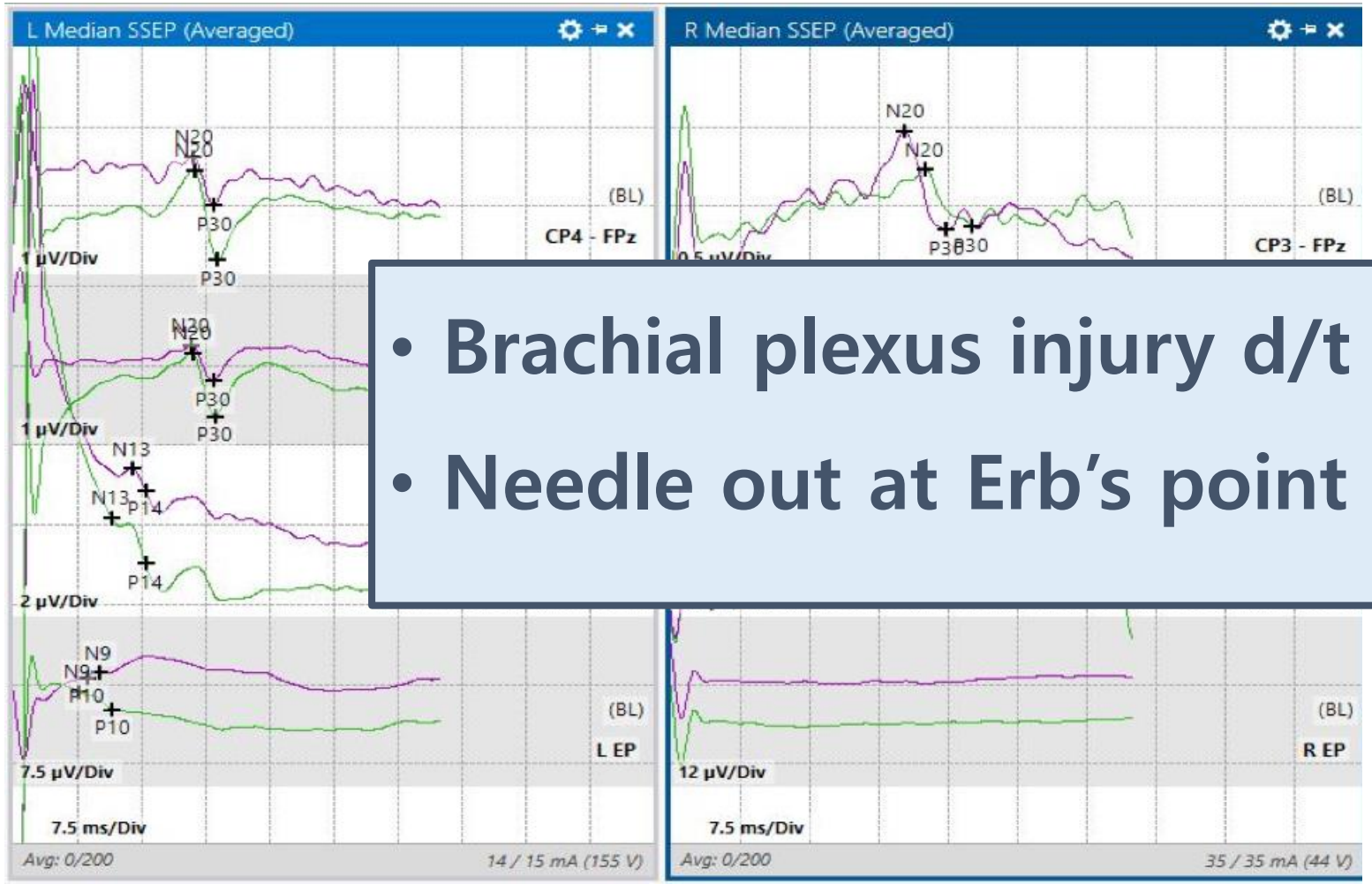
- Device
- Wrist malposition & Swelling

Scalp Cortical function

function

Erb's Brachial Plexus

SEP



- Brachial plexus injury d/t malposition
- Needle out at Erb's point

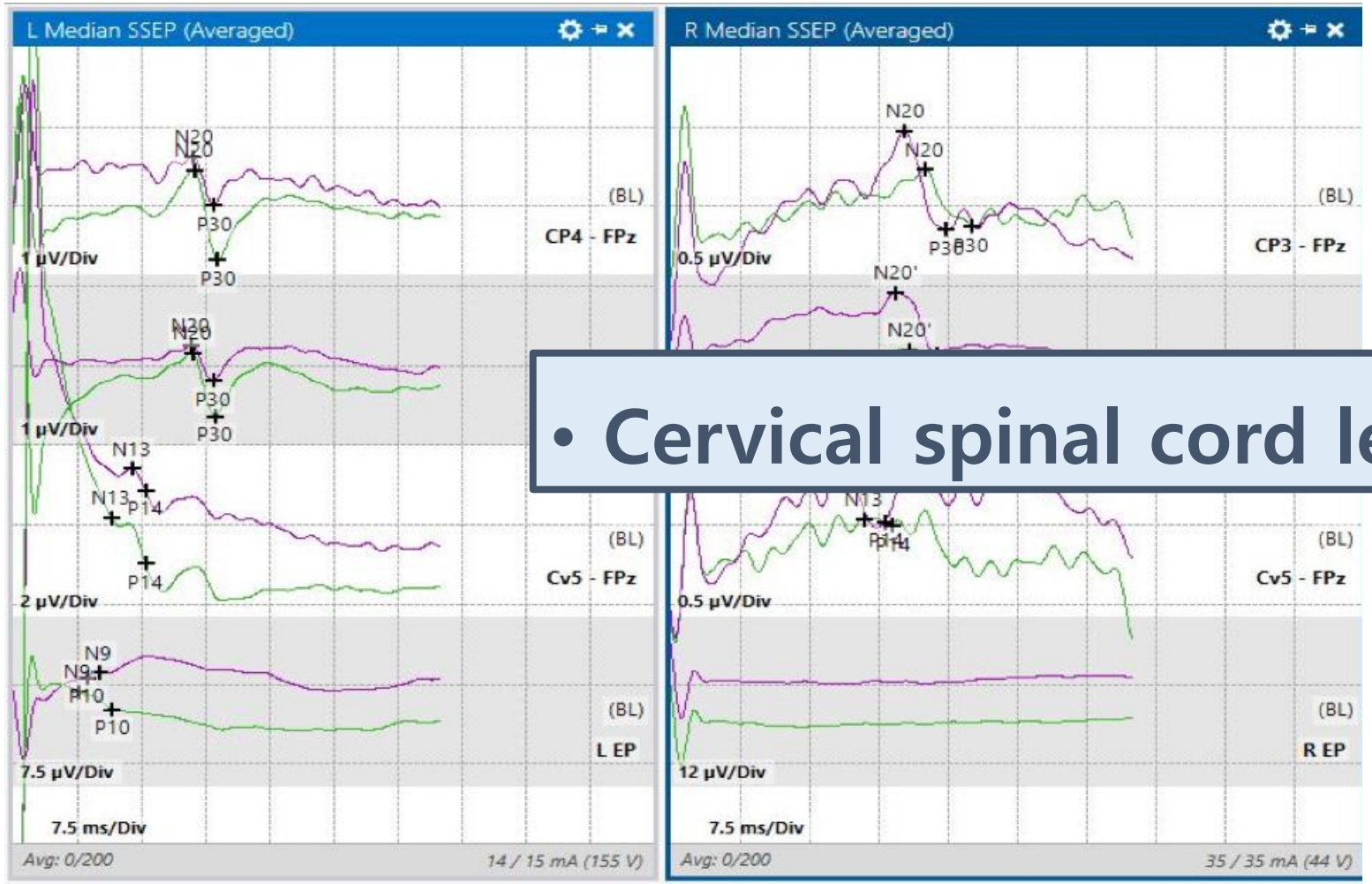
Scalp Cortical function

l function

tem

Erb's B n Plexus

SEP



- Cervical spinal cord lesion

Scalp Cortical function

Cortical function

C5s

Erb's Plexus

SEP

- Needle out at FPz

Scalp Co function

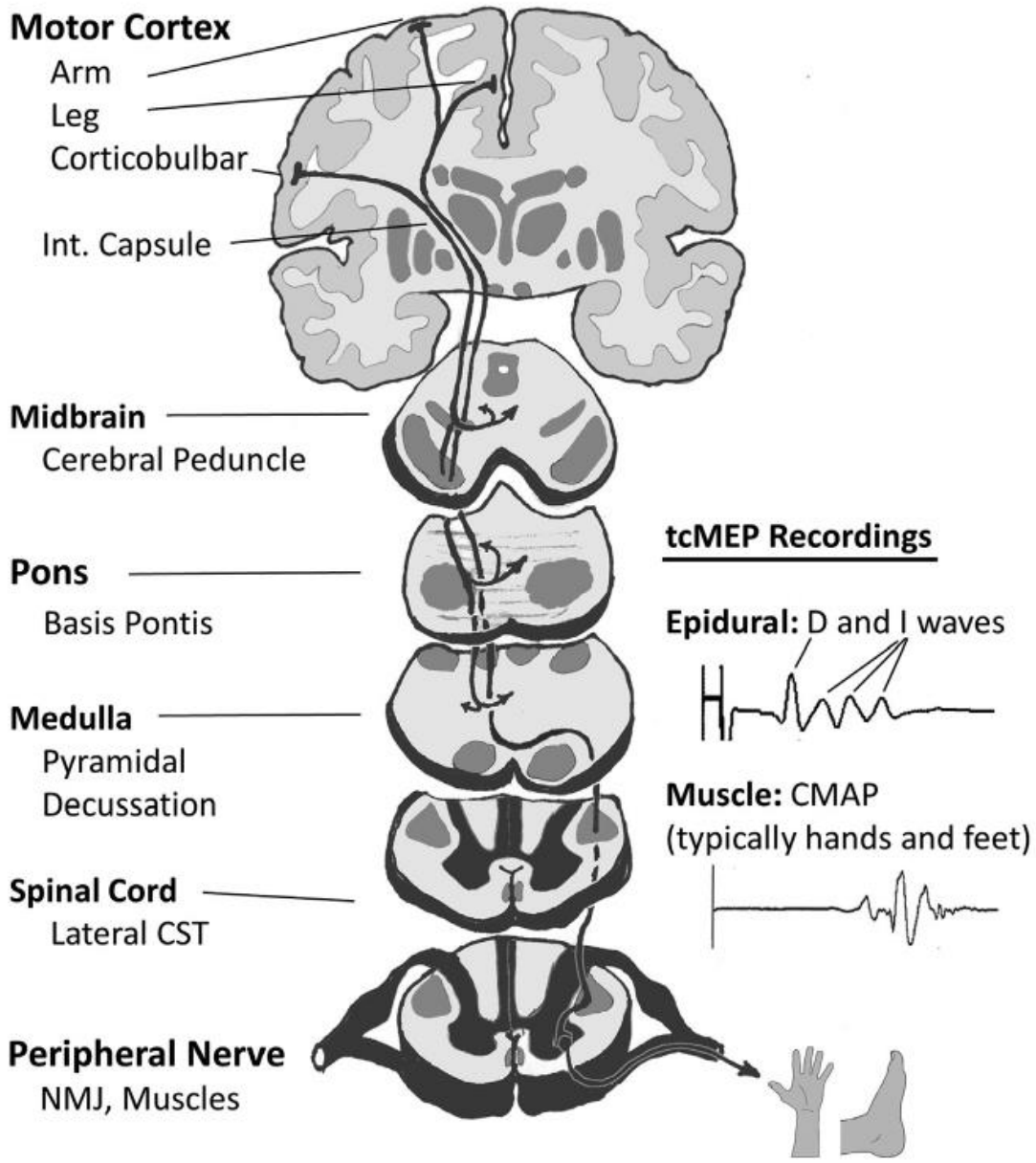
Scalp Cortical function

C5s Brainstem

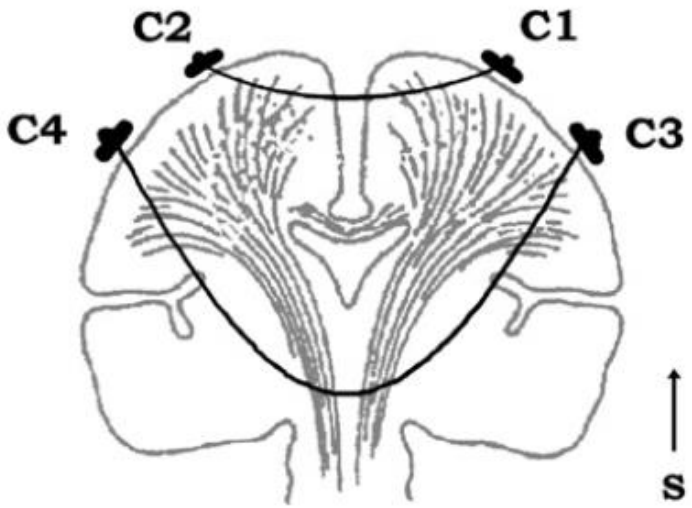
Erb's Brachial Plexus

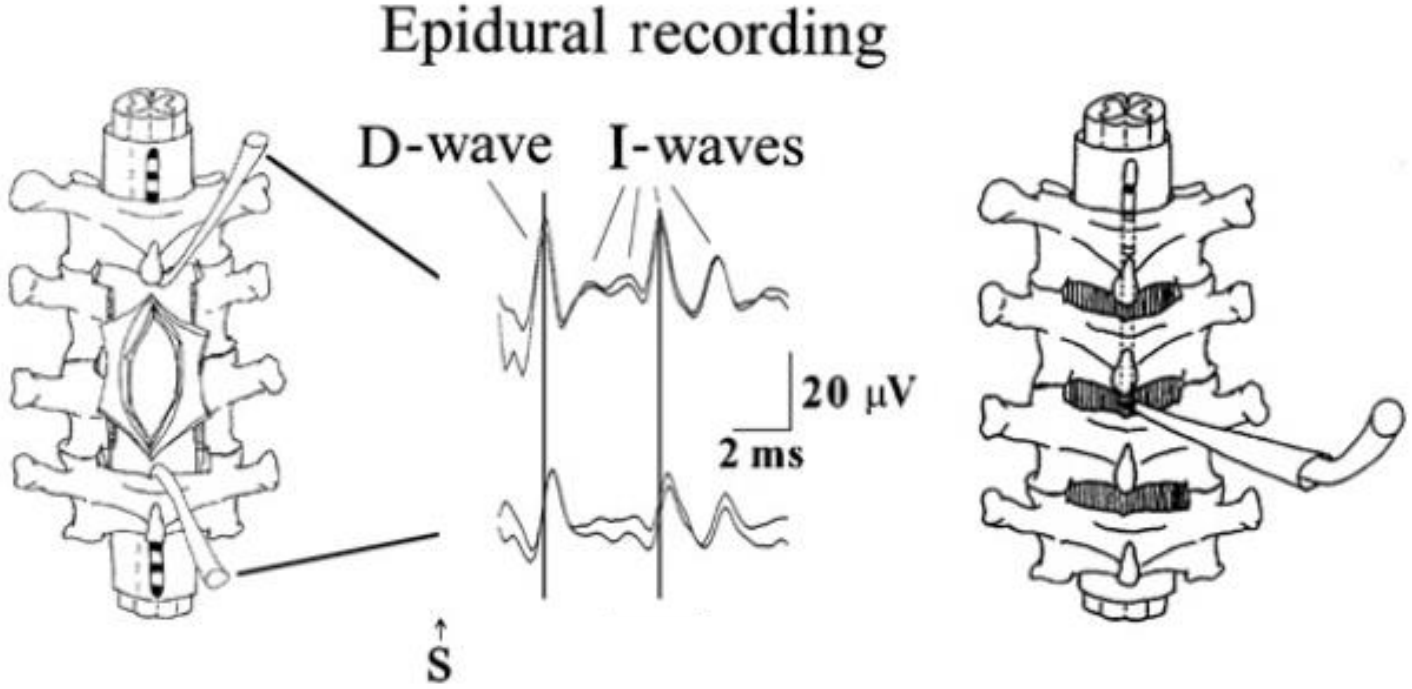
Trancranial MEP

- Corticospinal tract
- **Anterior Horn Cell**
  - Epidural recordings
  - Muscle recordings

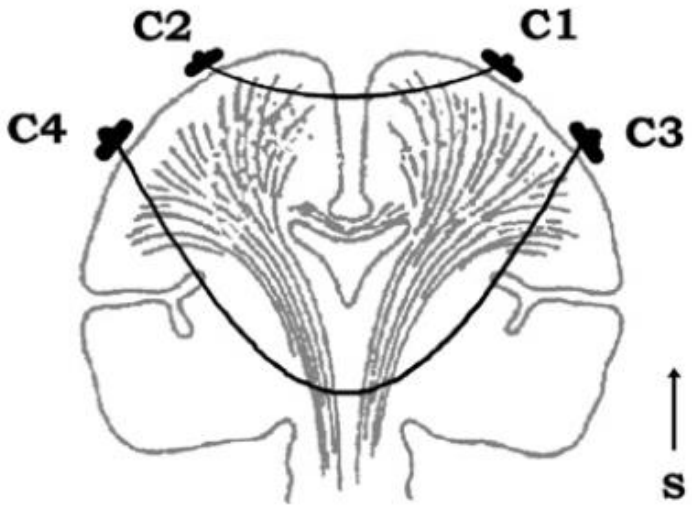


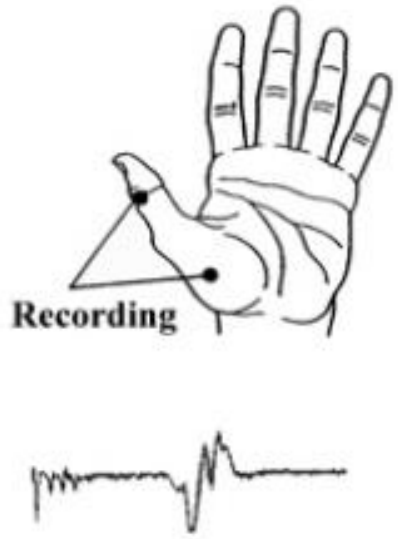
Transcranial MEP



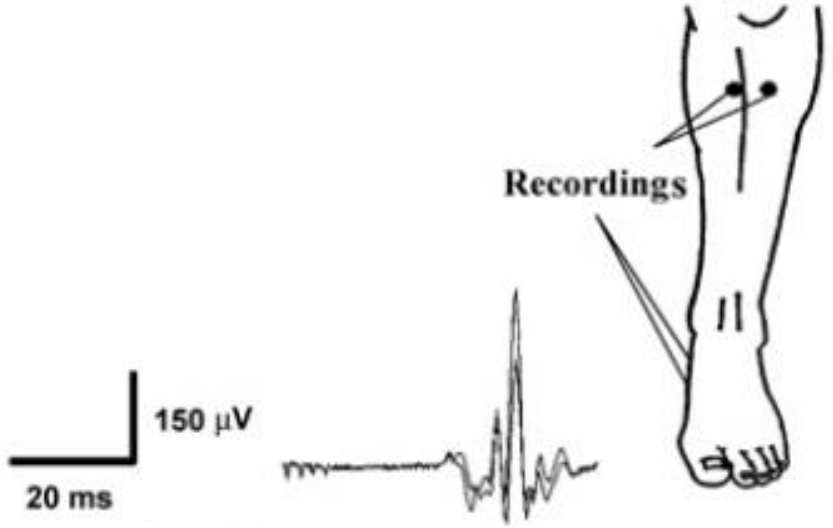


Transcranial MEP



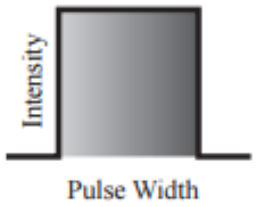


Muscle recording



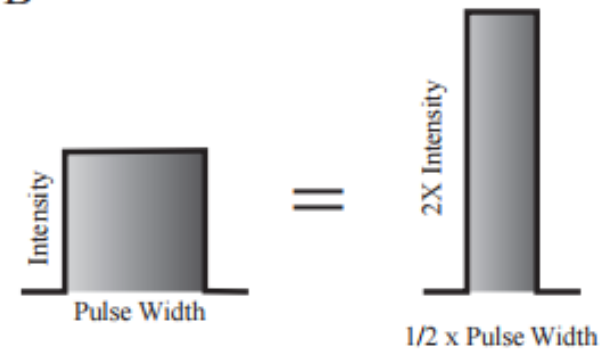
MEP stimulation parameter

A

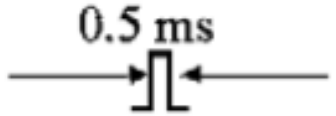


Power = Intensity x Pulse Width

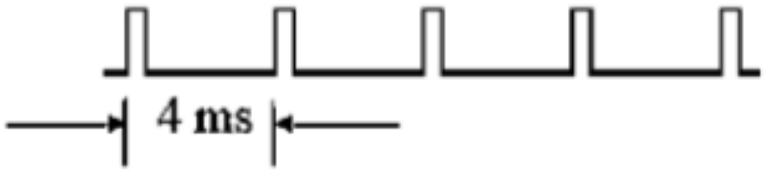
B



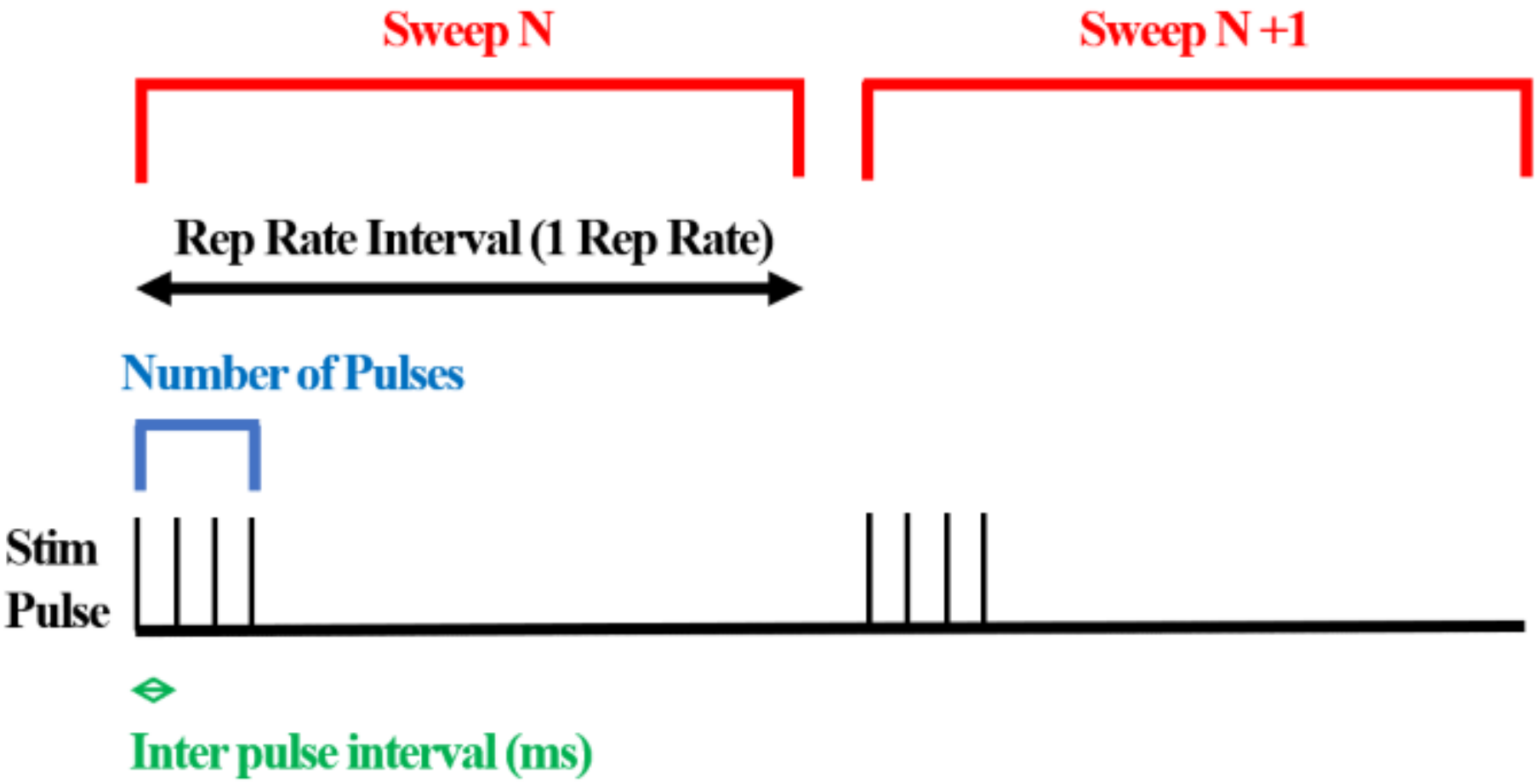
Single Stimulus Technique



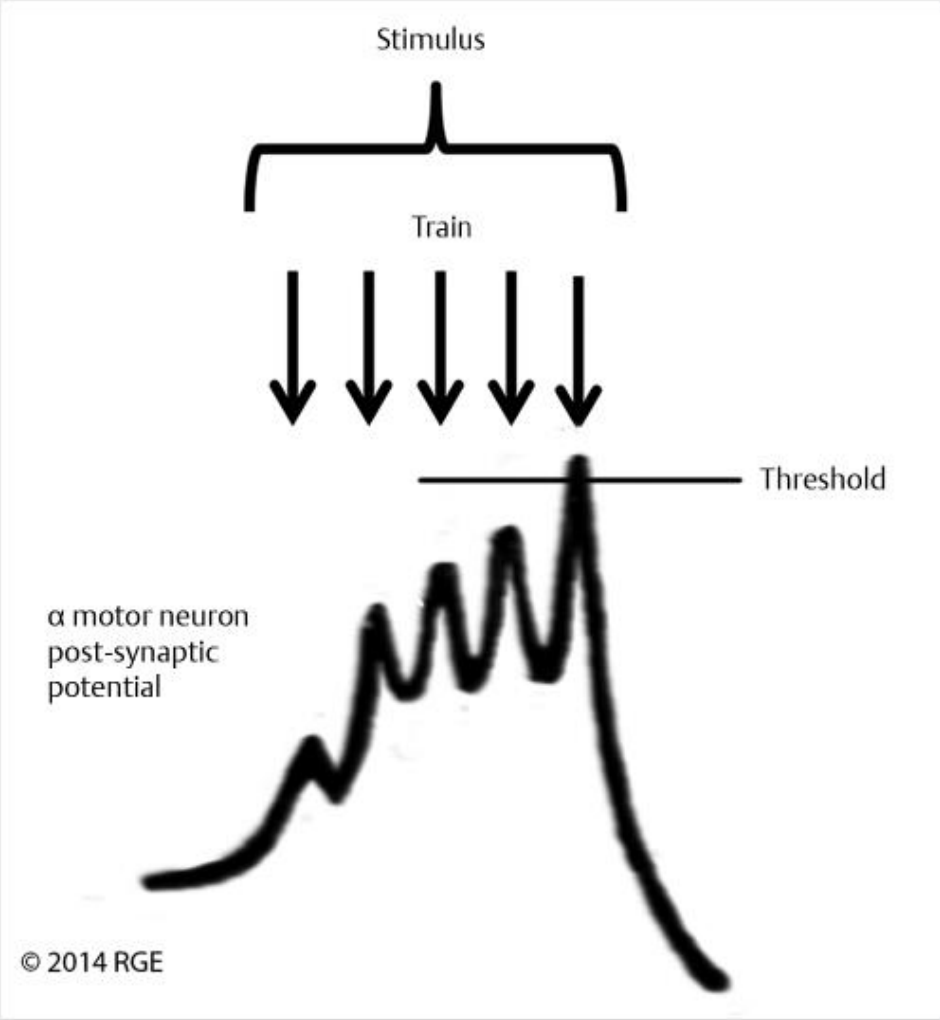
Train Stimulus Technique

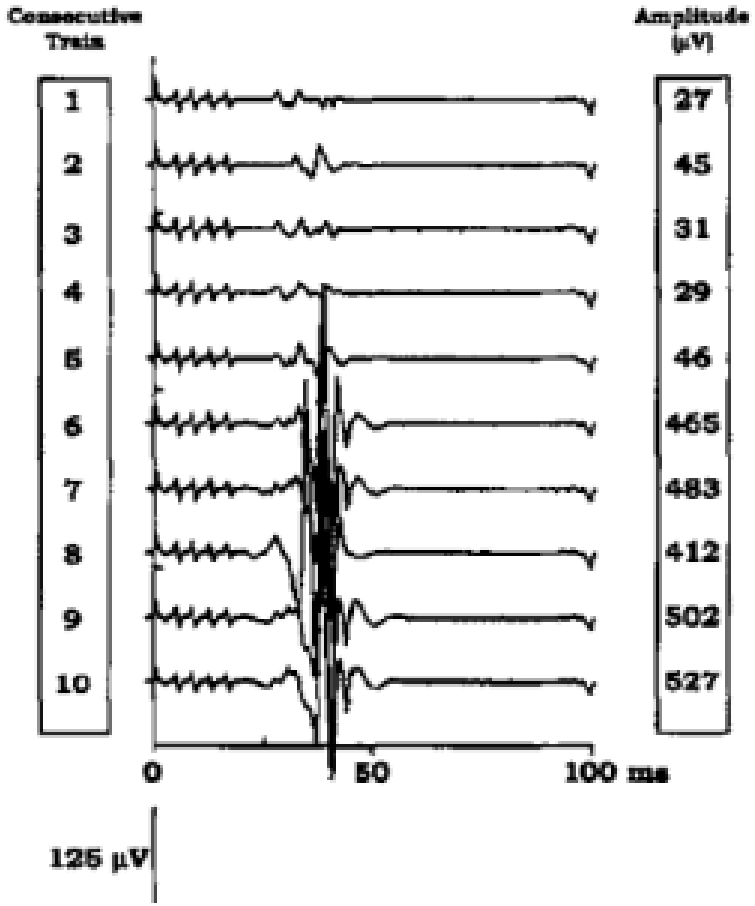


MEP stimulation parameter



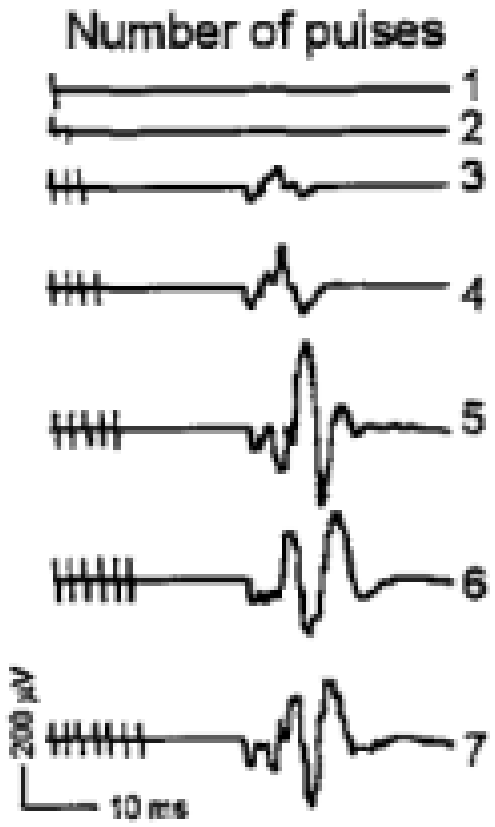
MEP stimulation parameter

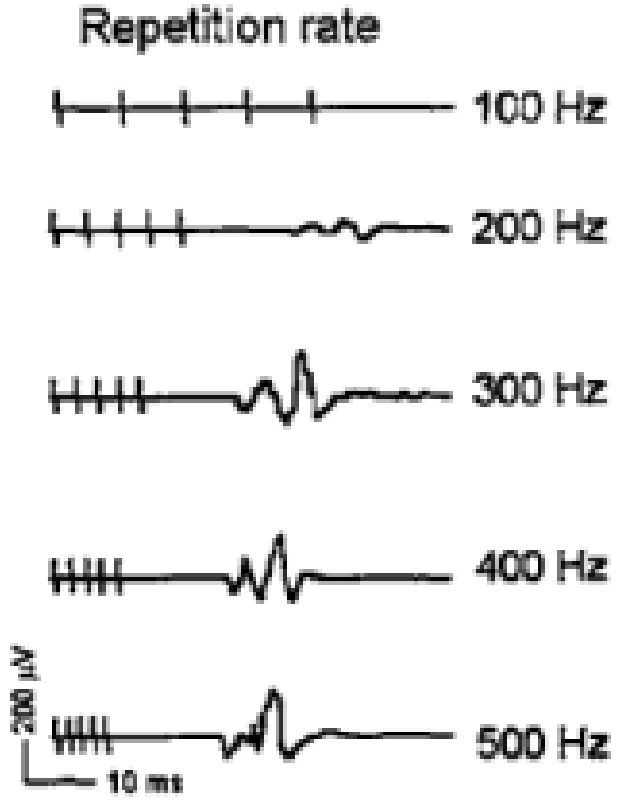


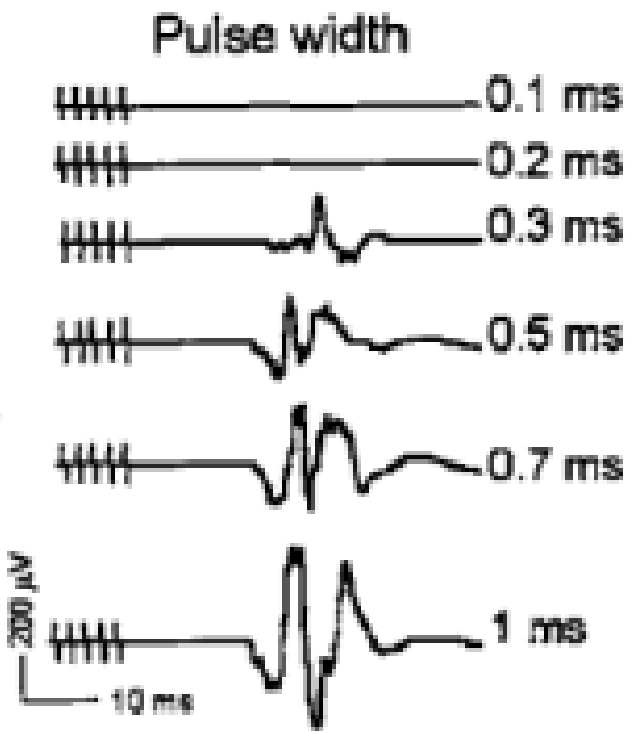


MEP stimulation parameter

MEP stimulation parameter



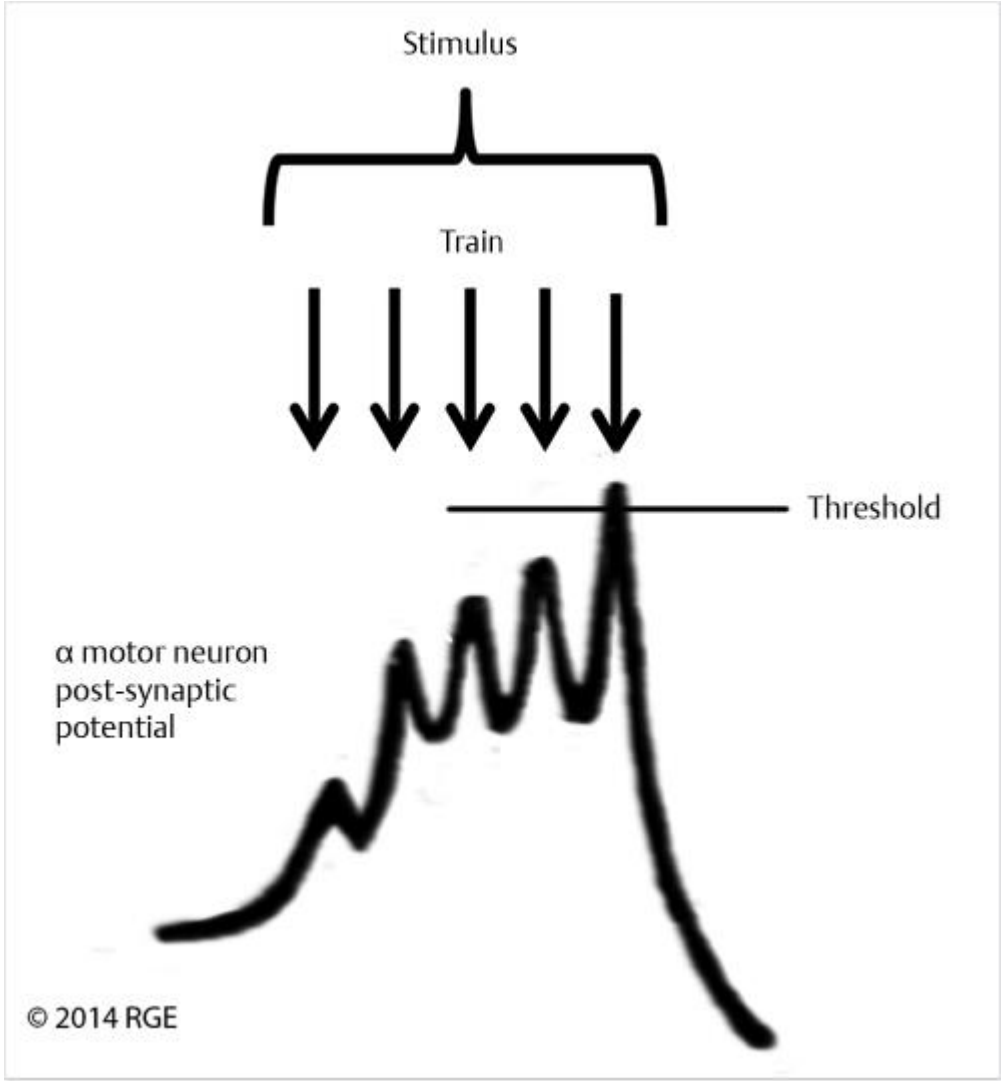




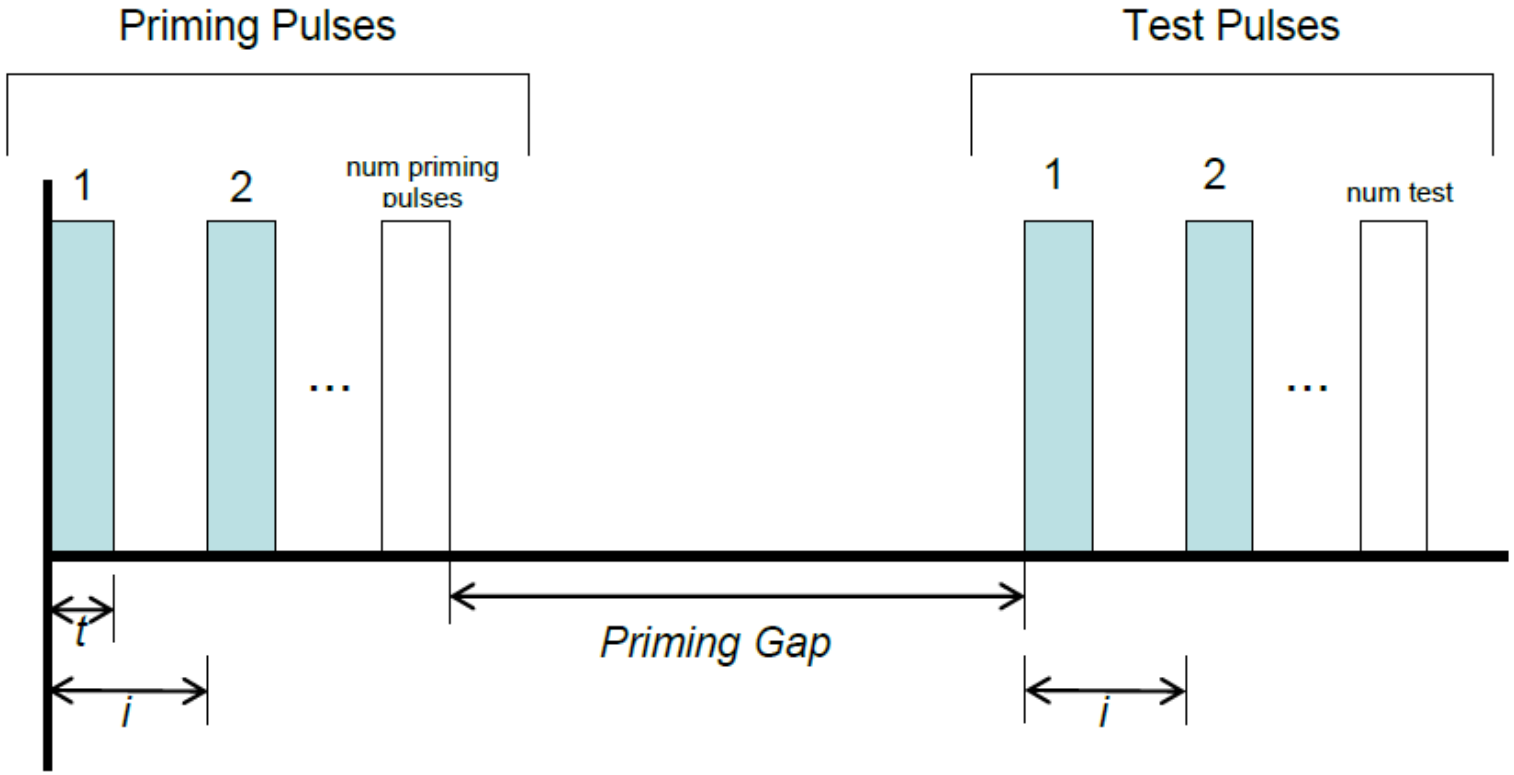
MEP stimulation in vulnerable patient

- **Excitatory Post-Synaptic Potential**

- Facilitation
- Prime

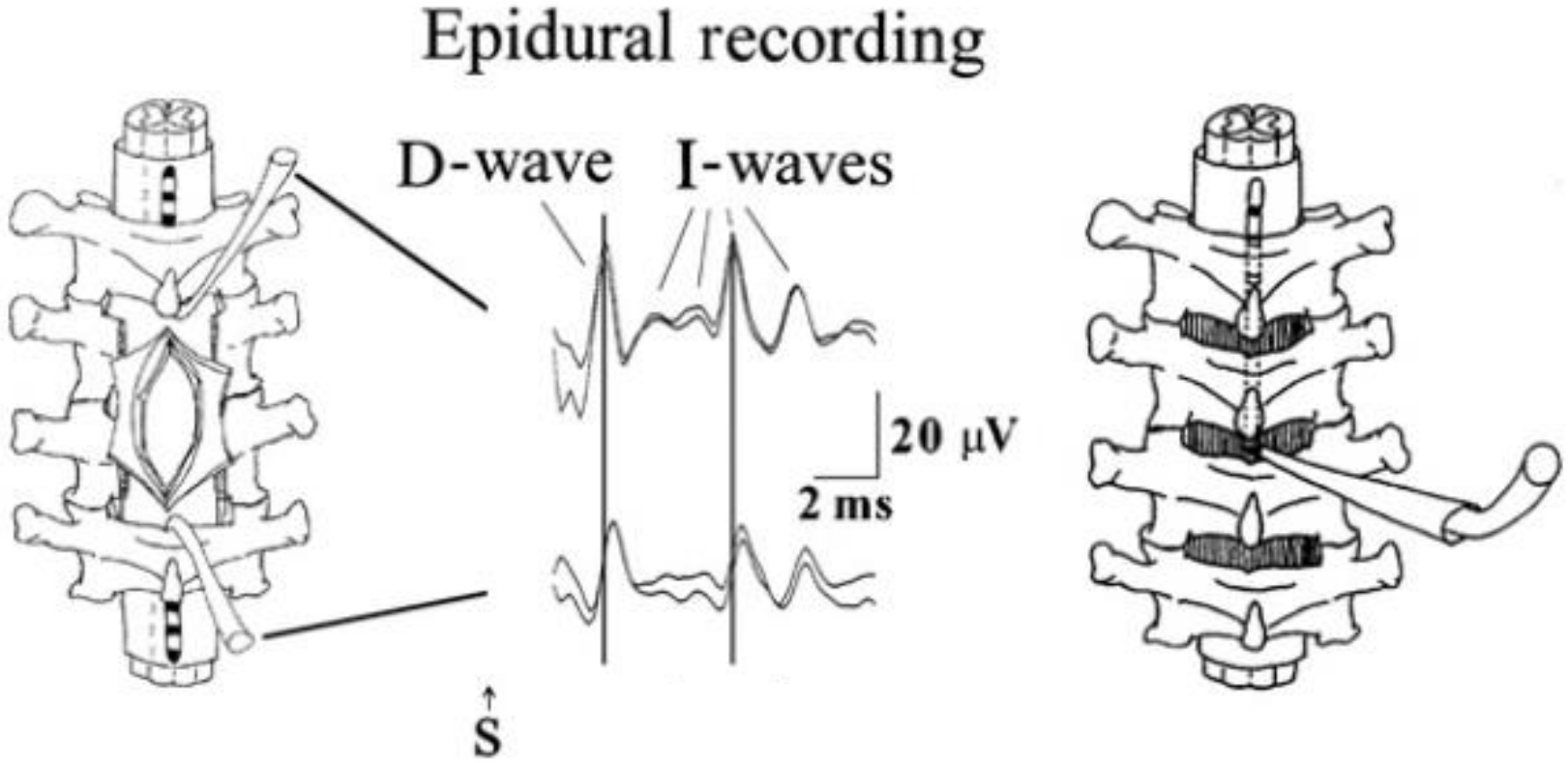


MEP stimulation in vulnerable patient

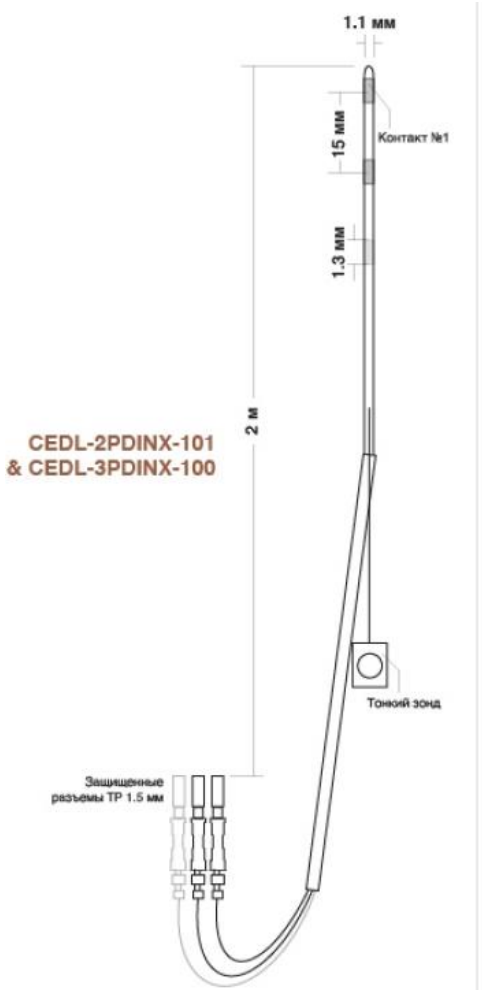


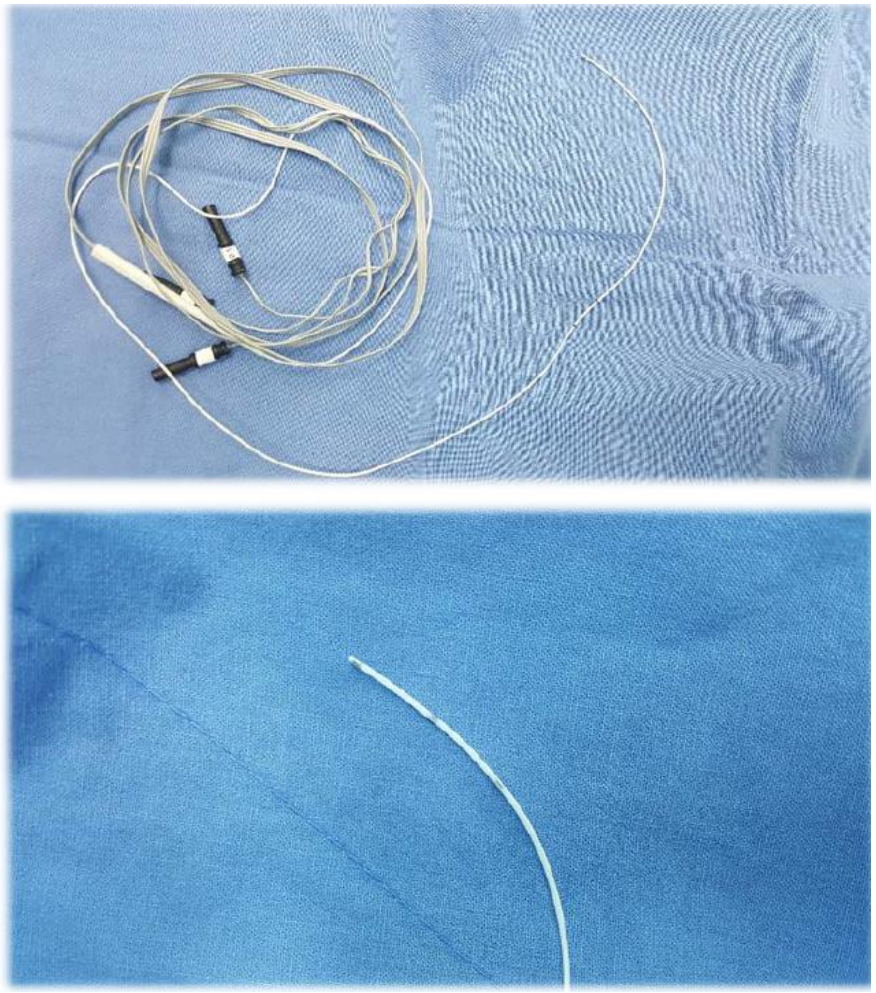
t = Pulse Duration – Fixed at 50us
i = Interpulse Interval (pulse rate)
Note: Num Priming Pulses + Num Test Pulses cannot exceed 9 total.

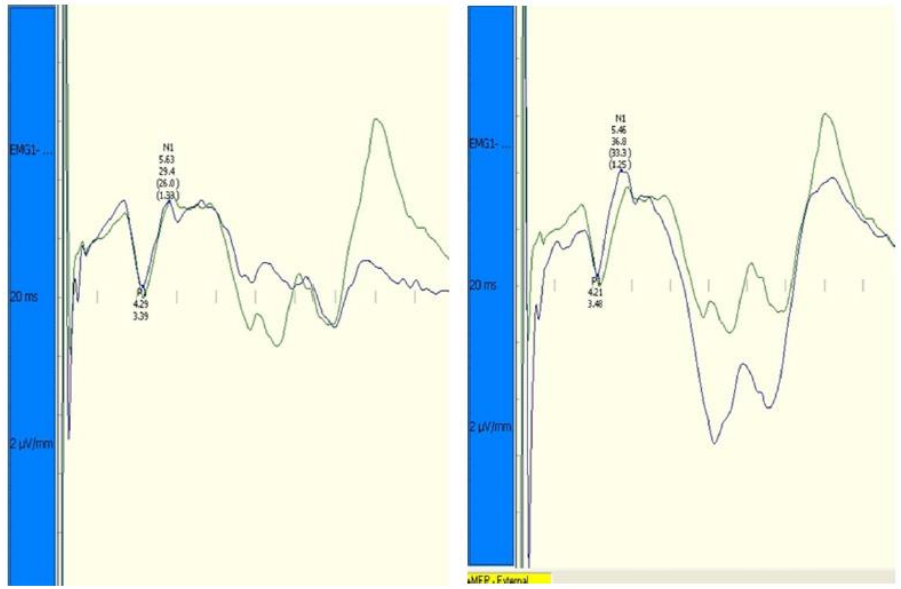
D wave



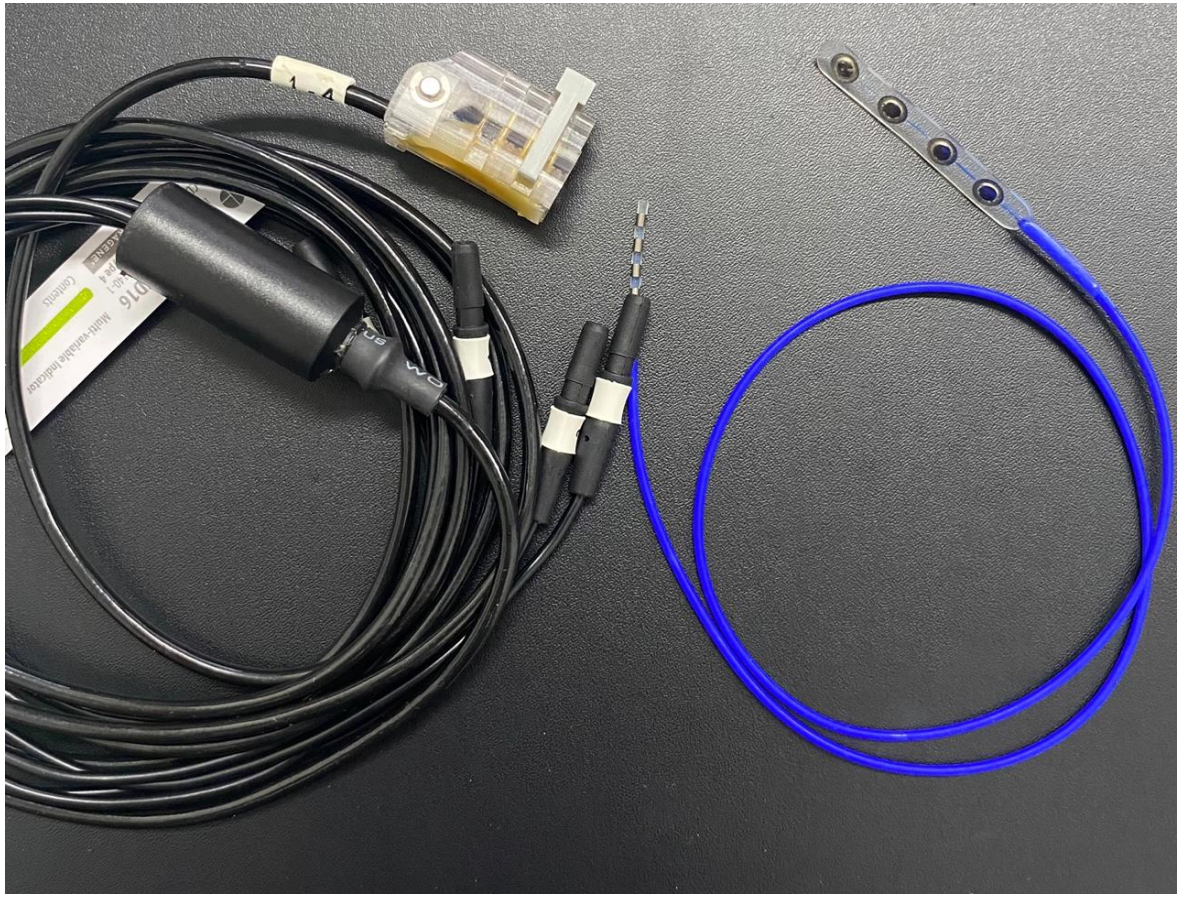
D wave

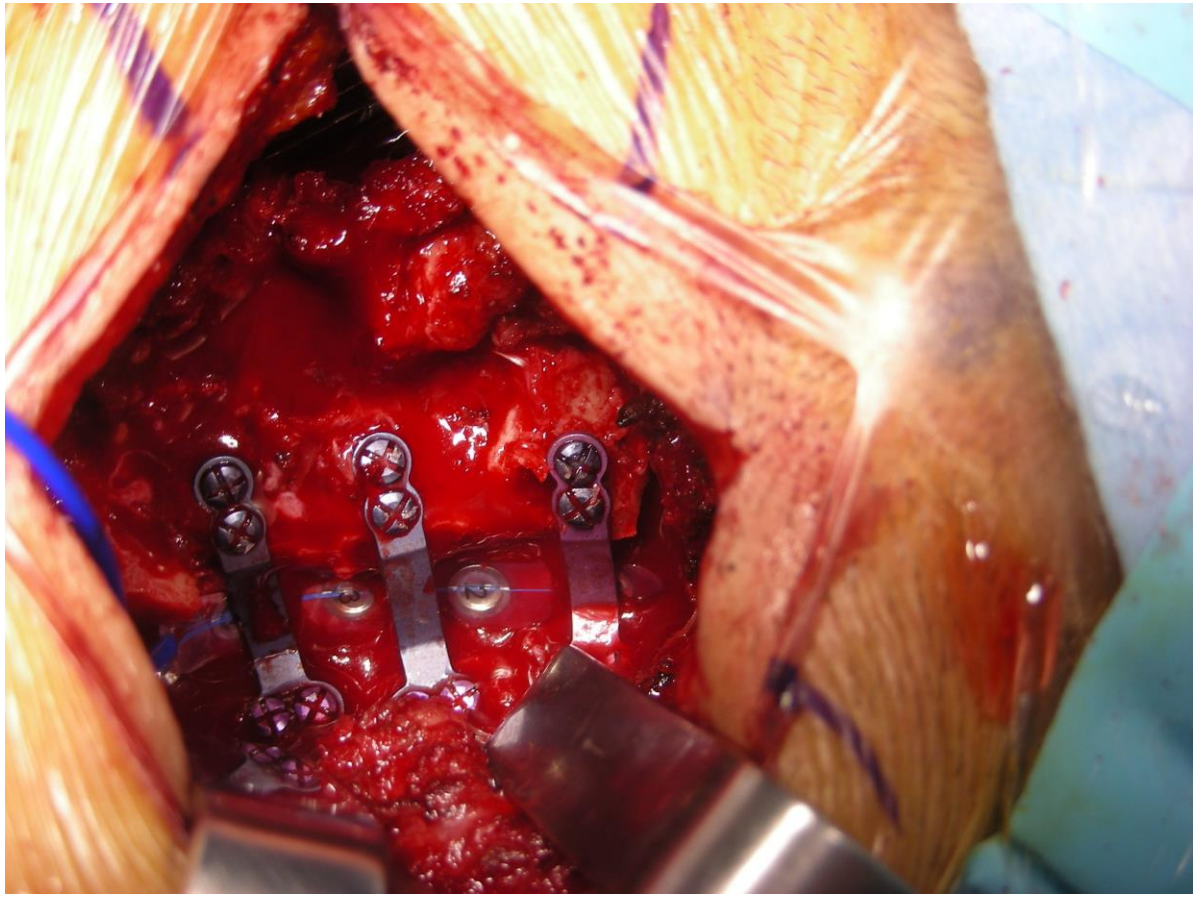

1.1 мм
15 мм
Контакт №1
1.3 мм
2 м
CEDL-2PDINX-101
& CEDL-3PDINX-100
Тонкий зонд
Защищенные
разъемы TP 1.5 мм




EMG1- ...
20 ms
2 µV/mm
N1
5.63
29.4
(26.0)
(1.38)
P1
4.29
3.39
EMG1- ...
20 ms
2 µV/mm
N1
5.46
36.0
(33.3)
(1.25)
P1
4.21
3.48

D wave





D wave

Advantages	Disadvantages
Relatively immune to anesthesia	**Unclearly localization**
Rapid reproducibility	No synaptic activity
Excellent correlation to motor outcome	**Invasive electrode complication**

Alarm Criteria Amplitude reduction > 50%

Muscle MEP

Spinal root myotomes

C1 – None

C2 – Sternocleidomastoid

C3 – Trapezius, sternocleidomastoid

C4 – Trapezius, levator scapulae

C5 – Deltoid, biceps

C6 –Biceps, triceps, brachioradialis, pronator teres, flexor carpi radialis (FCR)

C7 –Triceps, pronator teres, FCR, forearm extensors

C8 –Triceps, ulnar forearm muscles, all hand intrinsic muscles (incl. abductor pollicis brevis, first dorsal interosseous, adductor digiti minimi)

T1 –Hand intrinsic muscles, flexor carpi ulnaris

T2,T3, T4, T5, T6 – Intercostal muscles, paraspinal muscles

T6,T7, T8 – Upper rectus abdominis, paraspinal muscles, intercostal muscles

T8,T9, T10 – Middle rectus abdominis, paraspinal muscles, intercostal muscles

T10, T11, T12 – Lower rectus abdominis, paraspinal muscles, intercostal muscles

L1 –Quadratus lumborum, paraspinals, cremaster ± iliopsoas ± internal oblique

L2 –Iliopsoas, adductor longus, quadriceps, adductor magnus

L3 –Quadriceps, adductor longus, adductor magnus, iliopsoas

L4 –Quadriceps, tibialis anterior, adductor longus, adductor magnus, iliopsoas

L5 –Tibialis anterior, peroneus longus, adductor magnus

S1 – Gastrocnemius, abductor hallucis

S2 – Gastrocnemius, abductor hallucis

S2–S5 – Anal sphincter, urethral sphincter

Muscle MEP

5 pulses with 4 ms IPI

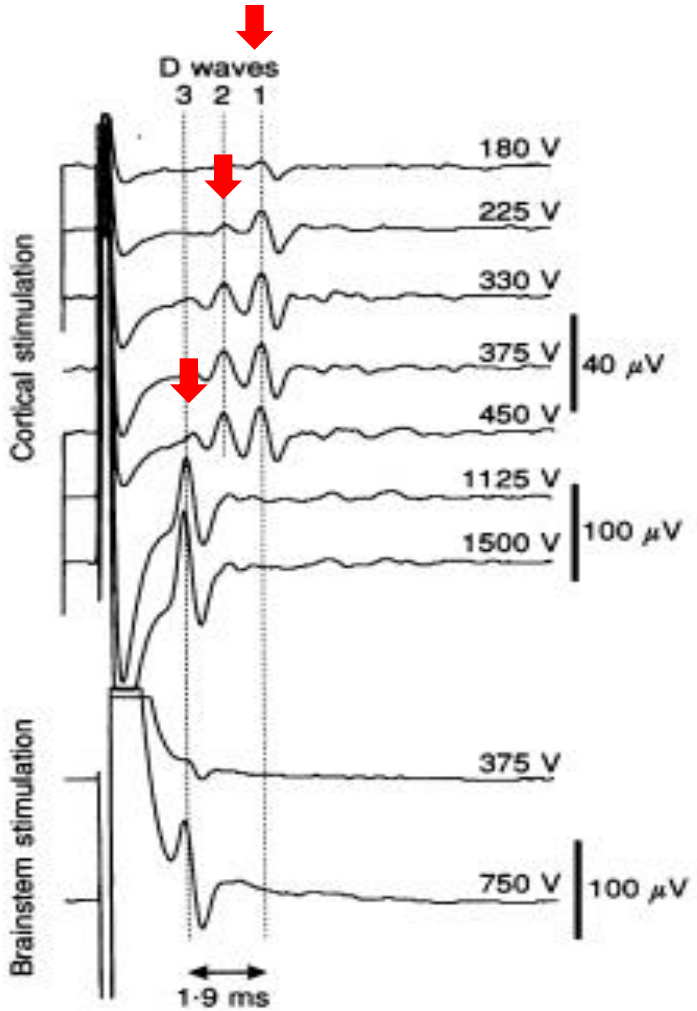
(Good starting point for spine surgery)

Published Stimulus Parameters
3 – 8 rectangular pulses
1 – 5 ms IPI
75 – 900 V (up to 0.9 A) intensity

Muscle MEP

Spine	Brain
Increasing the intensity of stimulation gradually	If possible, **avoid increasing the intensity of stimulus**
The MEP wave is interfered by the surgical procedure	It is possible to happen **false negative results** because of **activation in deeper subcortical motor pathway**

Excitation of the CT axons

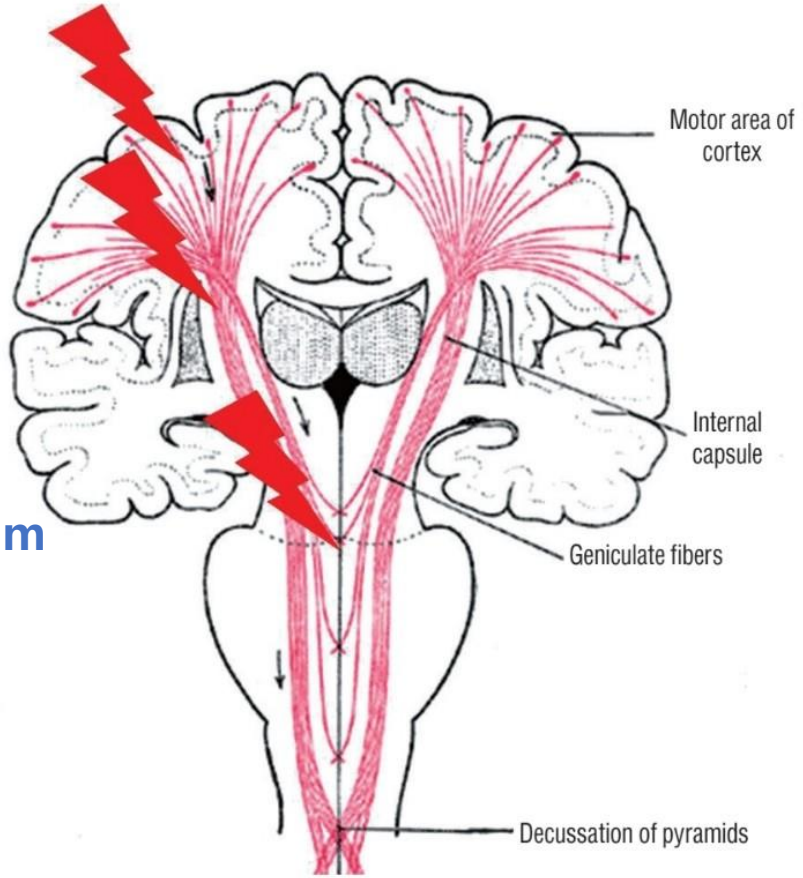


(Rothwell et al, 1994)

Cortex/Subcortex

Internal Capsule

Brainstem/Foramen magnum



Alarm criteria of muscle MEP

- Increases of **more than 100 V om the threshold** for obtaining of muscle MEP
- **Loss** of the muscle MEP
- **Amplitude reduction > 50 %**
- **Amplitude reduction > 80 %**

Safety & Complication of MEP

Stimulation Limitations of the TcMEP Modality

Energy limitation per pulse

50mJ per pulse on a 1000 Ohm Load (Safety requirement according to IEC60601-2-40 – collateral standard)

Energy limitation per time period

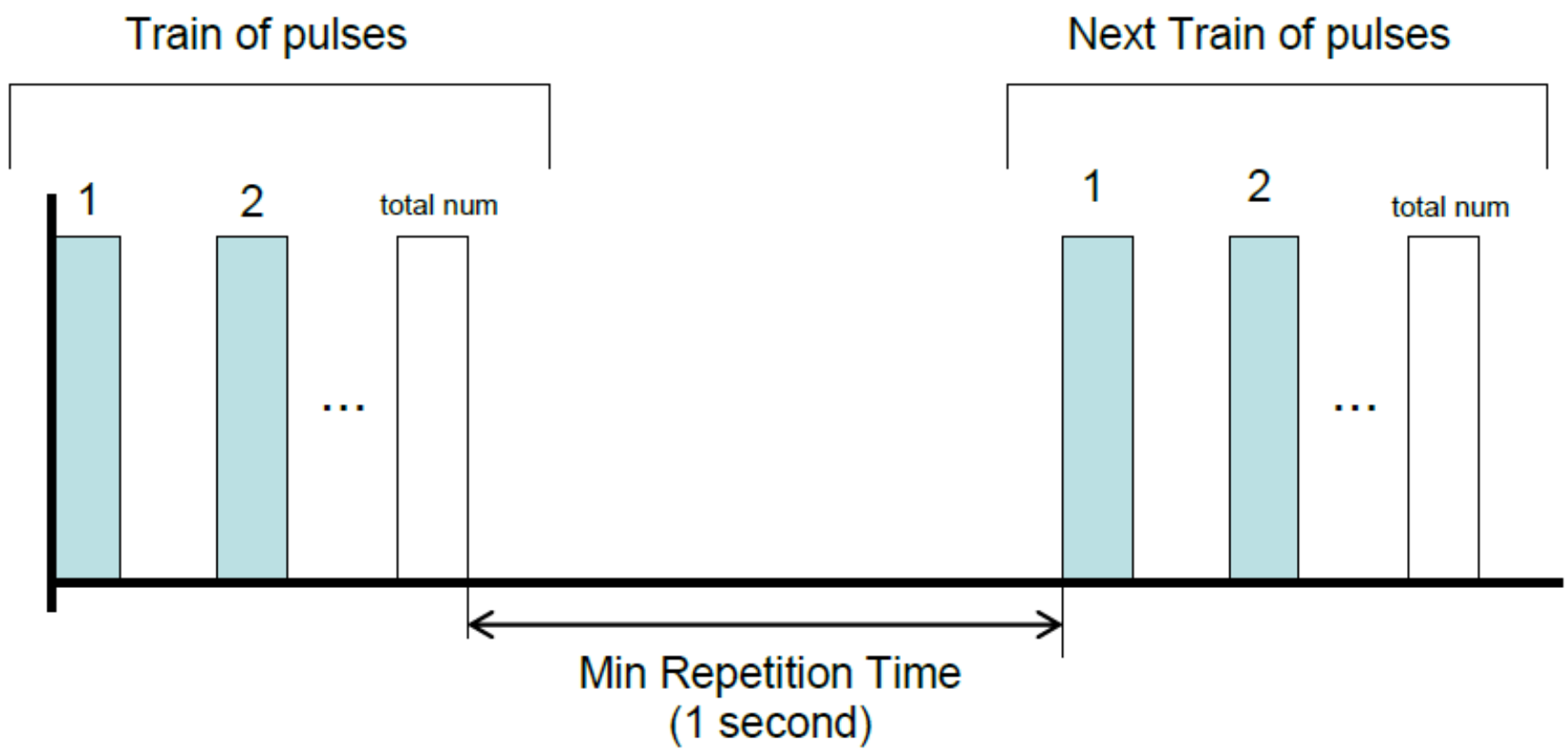
Maximum = 100mJ per second distributed in maximum 9 pulses on a 1000 Ohm load.

Safety & Complication of MEP

Voltage set [V]	TOTAL ENERGY [mJ]									RMS Voltage [$V_{R.M.S.}$]	RMS Current[1] [$A_{R.M.S.}$]
1000	50	100								10.00	0.0100
900	40.5	81								9.00	0.0090
800	32	64	96							9.80	0.0098
700	24.5	49	73.5	98						9.90	0.0099
600	18	36	54	72	90					9.49	0.0095
500	12.5	25	37.5	50	62.5	75	87.5	100		10.00	0.0100
400	8	16	24	32	40	48	56	64	72	8.49	0.0085
300	4.5	9	13.5	18	22.5	27	31.5	36	40.5	6.36	0.0064
200	2	4	6	8	10	12	14	16	18	4.24	0.0042
100	0.5	1	1.5	2	2.5	3	3.5	4	4.5	2.12	0.0021
0	0	0	0	0	0	0	0	0	0	0	0
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**		
	Number of pulses per train										

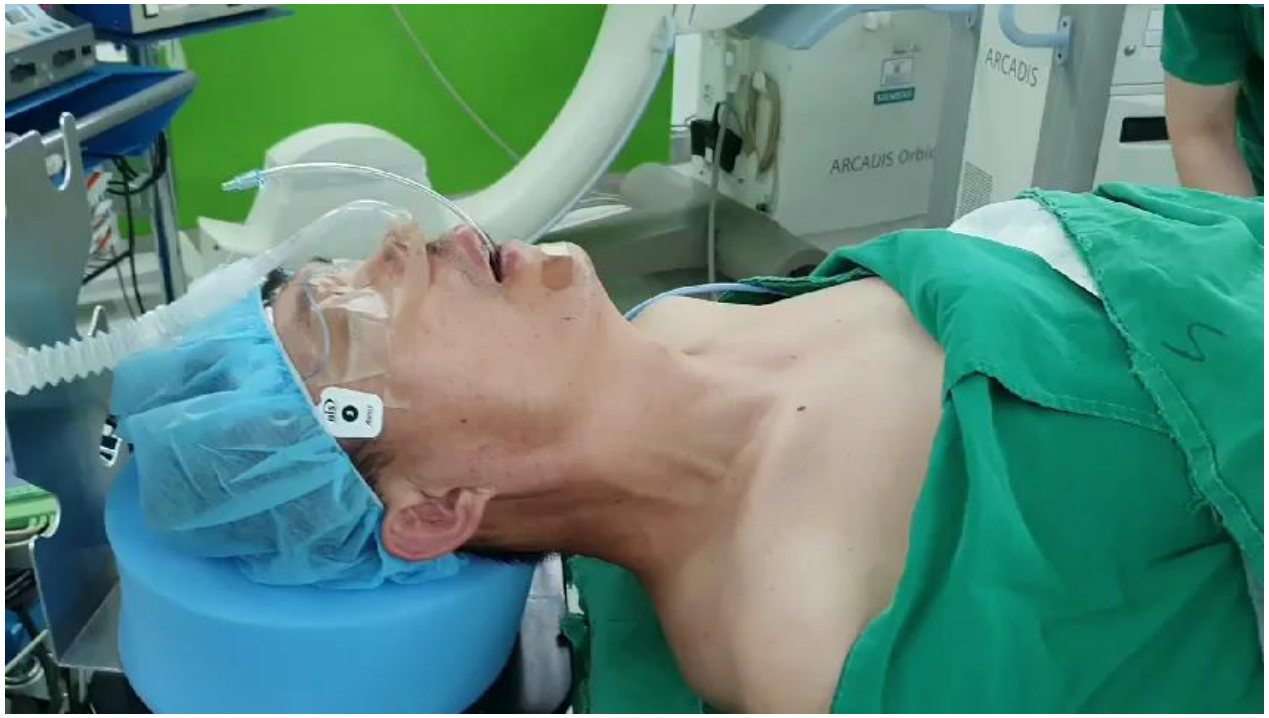
NOTES: [1] Calculated at the maximum number of pulses allowable per voltage settings

*Table 1: Total Energy per train, on a **1000Ohm** Load and **50us** pulse duration*

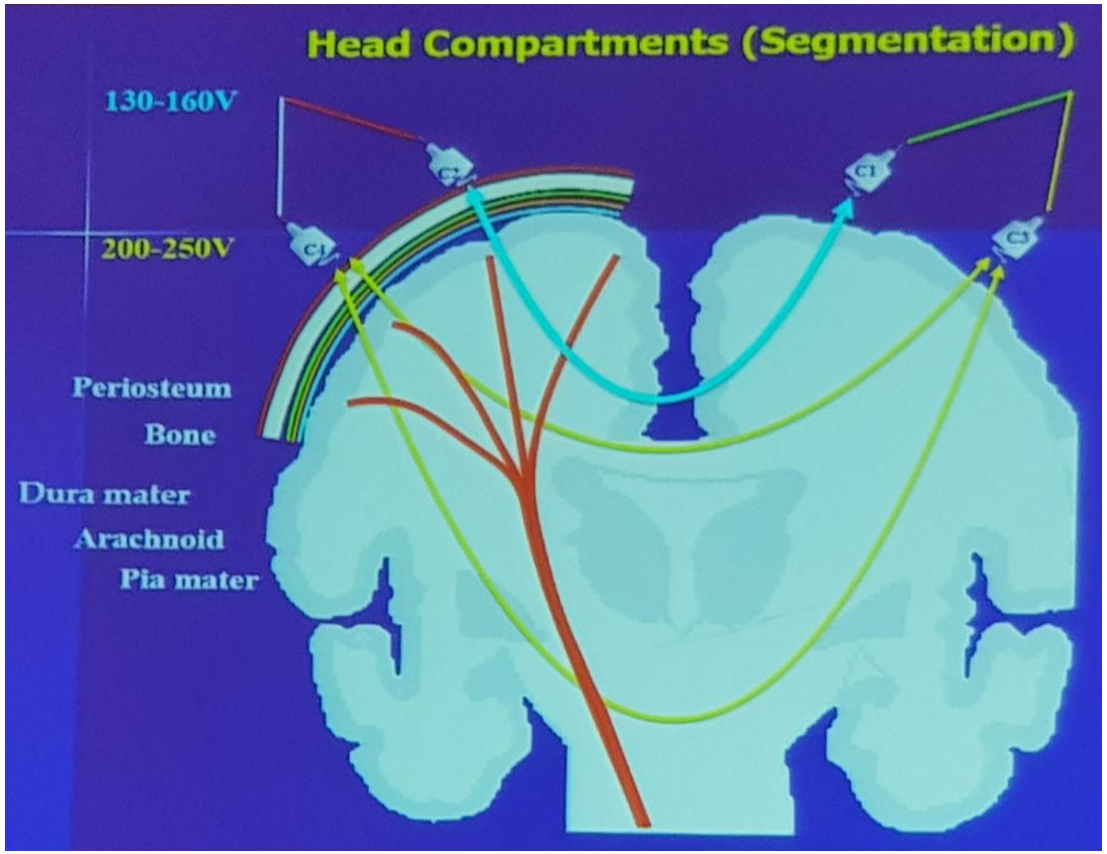

Train of pulses
Next Train of pulses
1
2
total num
...
1
2
total num
...
Min Repetition Time
(1 second)

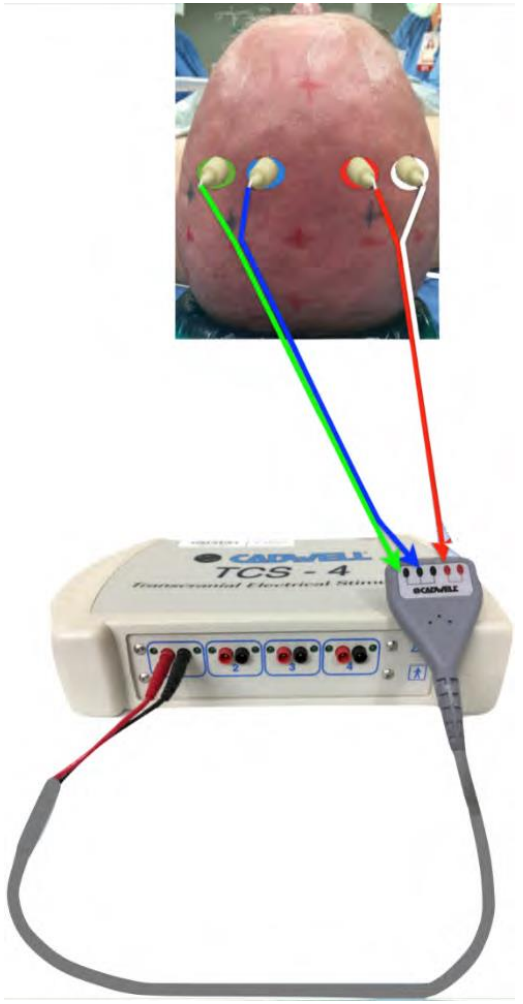
Safety & Complication of MEP

Adverse effects
Jaw contraction (→ Tongue bite)
Seizure
Pacemaker with implanted defibrillator (Very high risk of motor injury)
Scalp Burn
Head movement



Linked Quadri-Polar TcMEP

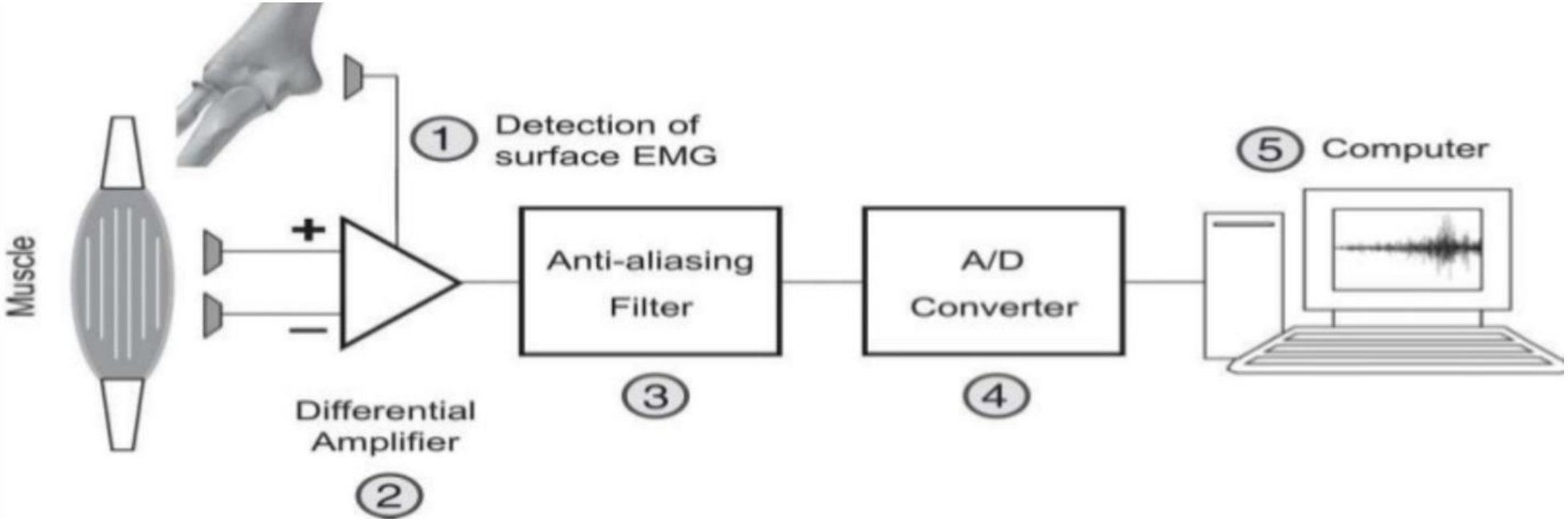




Neurological Monitoring Associates, LLC, Milwaukee, Wi

Electromyography (EMG)

- The recording of **compound muscle action potential (CMAP)** or **electrical activity** produced by **skeletal muscle**



Electromyography (EMG)

Motor Unit Action Potential (MUAP)

- Individual muscle fibers are organized into **motor units**, which are groups of muscle fibers that are activated by the same motor endplate.

Stimulation of an individual axon sufficient to reach the **threshold for action potential firing**

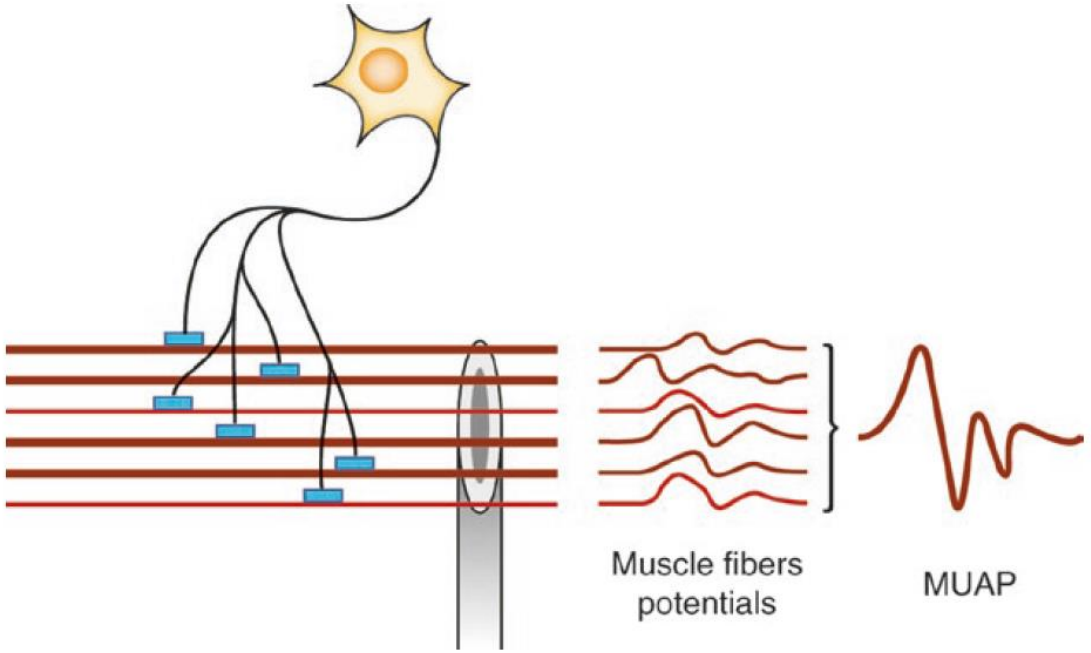
↓

Activation of a motor unit

↓

muscular contraction

- The individual muscle fiber action potentials can be recorded in **sum**, and this waveform is the motor unit action potential (MUAP)



Anatomical & Physiological Basis

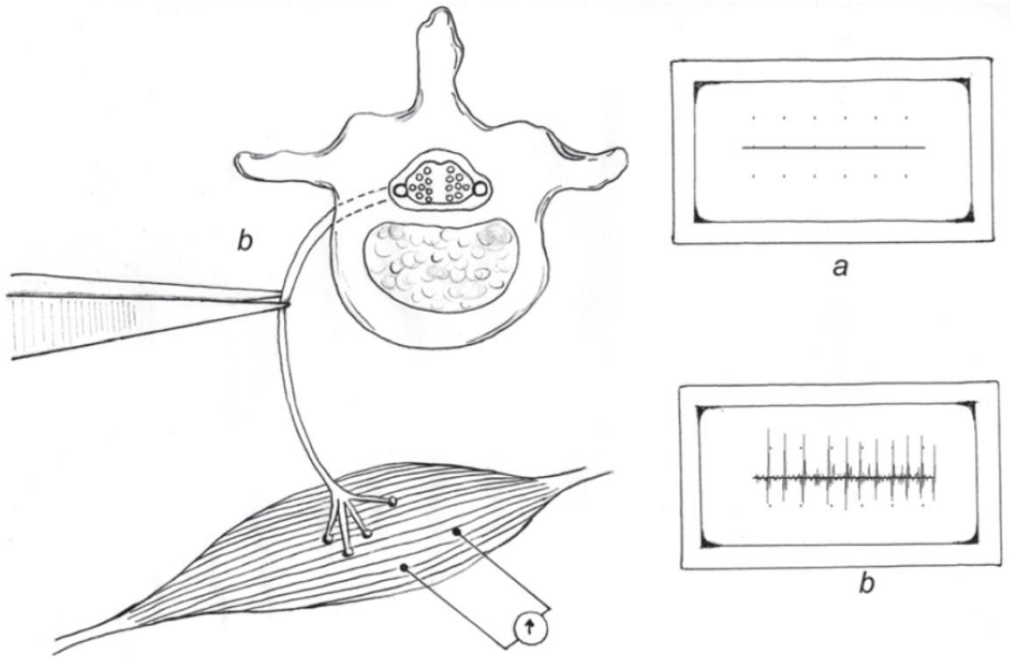
Surgical irritation of axon

Surgical irritation of axons is sufficient

Axonal depolarization

Activation of the muscle fibers

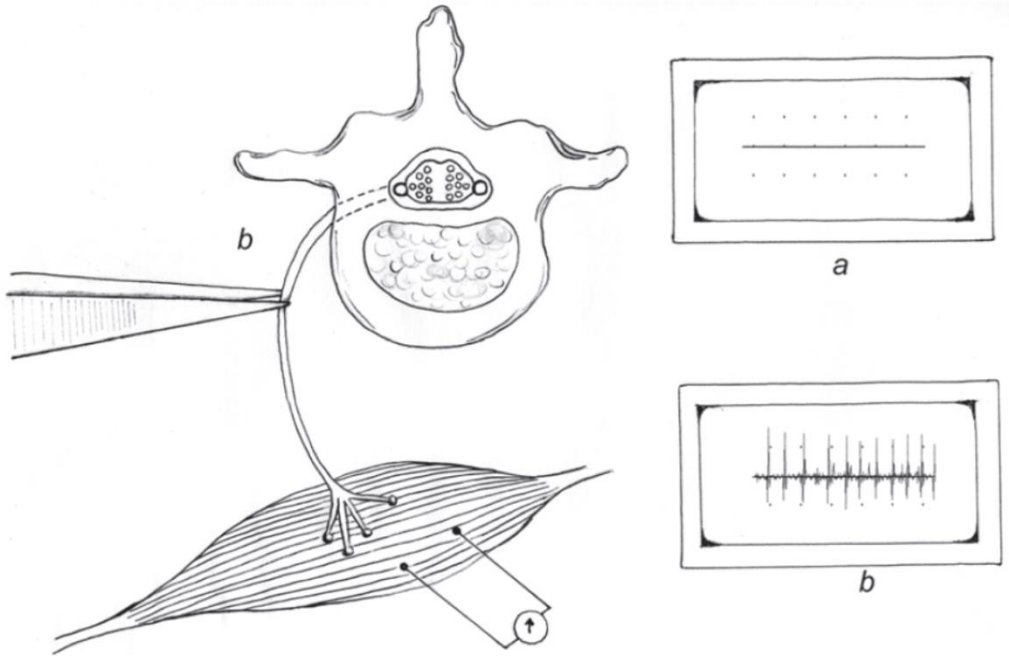
Depolarization of a single axon leads to single MUAP recorded as a “spike” on EMG



Anatomical & Physiological Basis

Surgical irritation of axon

- **Pre-existing** condition of the nerve
- **Degree** & **mechanism** of neural irritation
- **Integrity** of distal neuromuscular function



Electromyography (EMG)

Spinal root myotomes

C1 – None
C2 – Sternocleidomastoid
C3 – Trapezius, sternocleidomastoid
C4 – Trapezius, levator scapulae
C5 – Deltoid, biceps
C6 –Biceps, triceps, brachioradialis, pronator teres, flexor carpi radialis (FCR)
C7 –Triceps, pronator teres, FCR, forearm extensors
C8 –Triceps, ulnar forearm muscles, all hand intrinsic muscles (incl. abductor pollicis brevis, first dorsal interosseous, adductor digiti minimi)

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L3 –Quadriceps, adductor longus, adductor magnus, iliopsoas
L4 –Quadriceps, tibialis anterior, adductor longus, adductor magnus, iliopsoas
L5 –Tibialis anterior, peroneus longus, adductor magnus
S1 – Gastrocnemius, abductor hallucis
S2 – Gastrocnemius, abductor hallucis
S2–S5 – Anal sphincter, urethral sphincter

Intraoperative EMG monitoring

Free running EMG

Passive muscle recordings

Detecting irritation of
Cranial Nerve or
Spinal root

Stimulated EMG

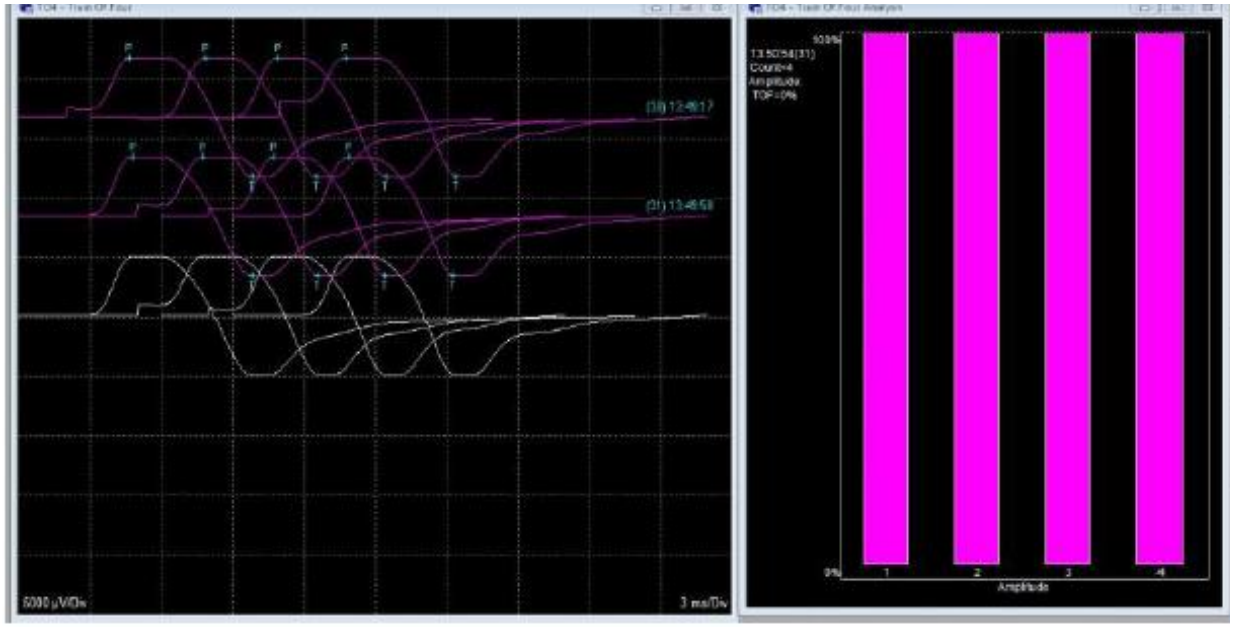
Electrical stimulation
of **neural elements** or
hardware

The purposes of
assessing function

Anesthesia

Neuromuscular blocker

- Significantly **attenuate motor activity**
- Should be **avoid** as much as possible
- **> 2 response (or 80%) Train of Four**



Free running (Spontaneous) EMG

Impending injury to spinal nerve	Rare firing
Stretch	**Heat & Cold exposure**
Compression	Age
Other forms of Mechanical irritation	**Pre-operative nerve injury**

Ischemia

- usually does not induce action potential firing
- poorly detected by EMG

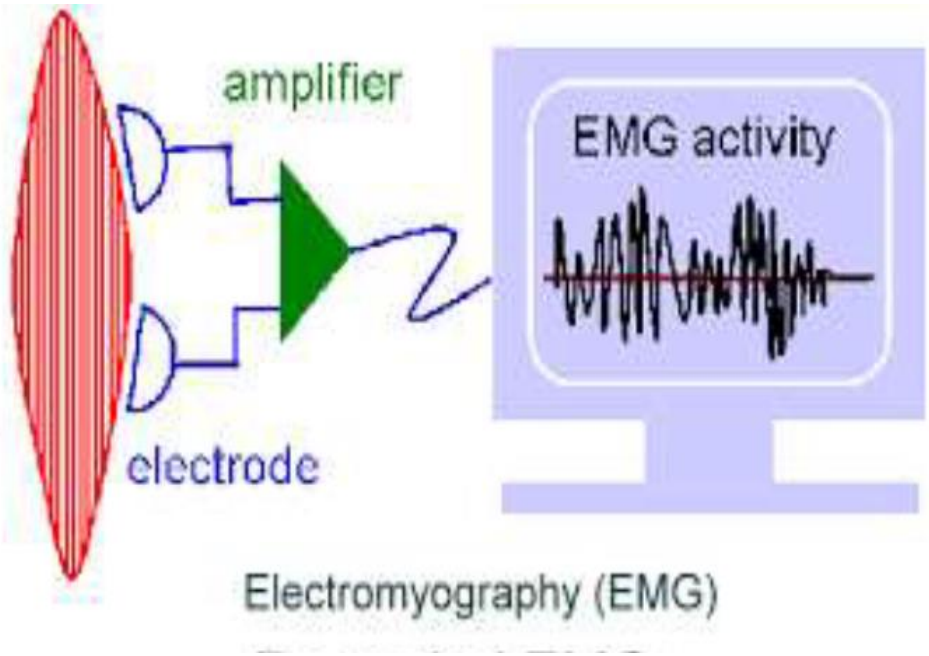
Free running (Spontaneous) EMG

Patterns of EMG activity

Motor Unit Action Potential (MUAP)

Neurotonic Discharge

Artifactual activity



Free running (Spontaneous) EMG

MUAP

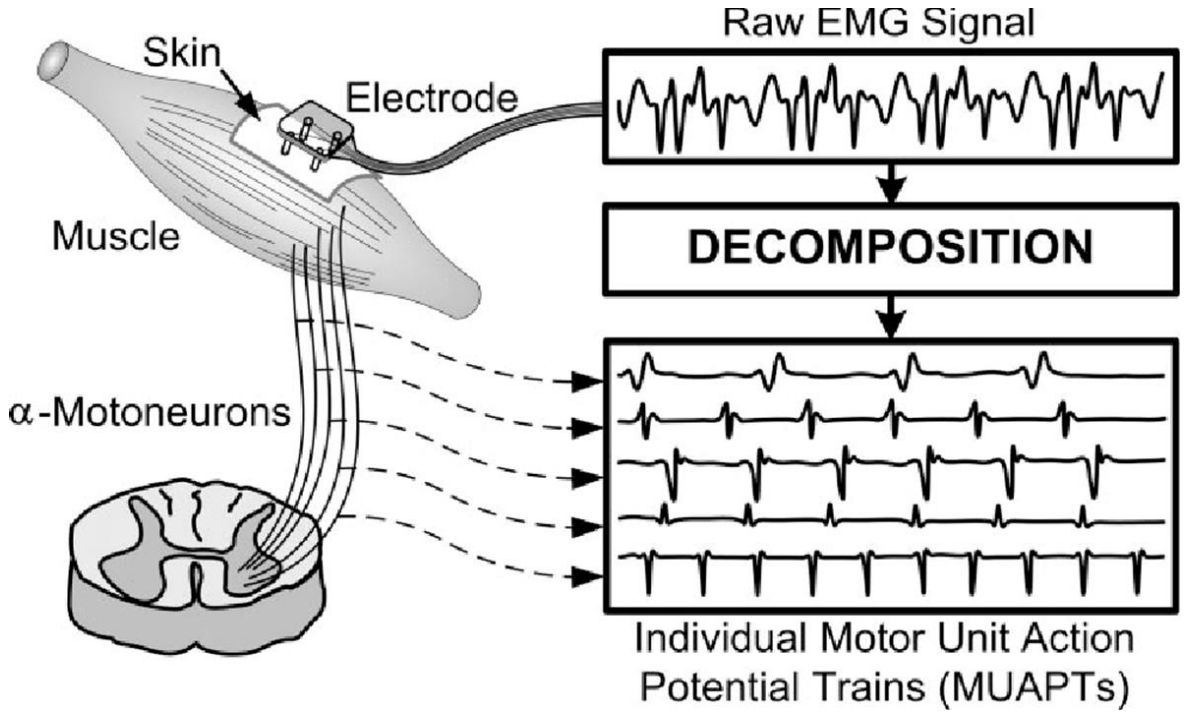
Reflex activity of anterior horn cells

Incomplete relaxation with voluntary firing

Increased muscle tone

Insufficient patient sedation

Semi-rhythmic pattern



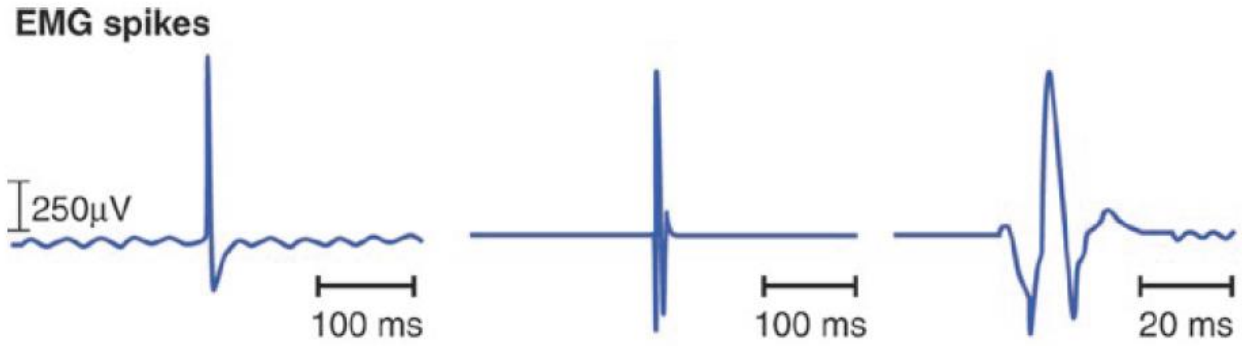
Free running (Spontaneous) EMG

Spike

- Random activation of one or a few **motor units** during surgery
  - Incidental contact with the neural elements

- No clinically significant

- **Bi-** or **tri**phasic potentials
- **one large peak** (≤ 2000 μV)



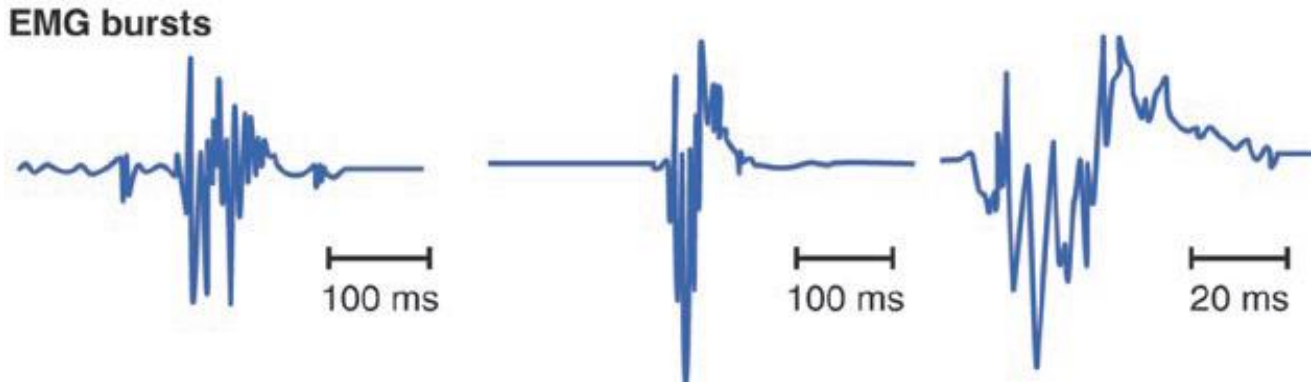
Free running (Spontaneous) EMG

Bursts

- Random activation of **several** **motor units**

- **Synchronous**
- **Nonrepetitive** discharges
- **Poly**phasic potentials
- > **5000** µV of amplitude

- **Mechanical contact activity**
- Free irrigation with Ringer's solution



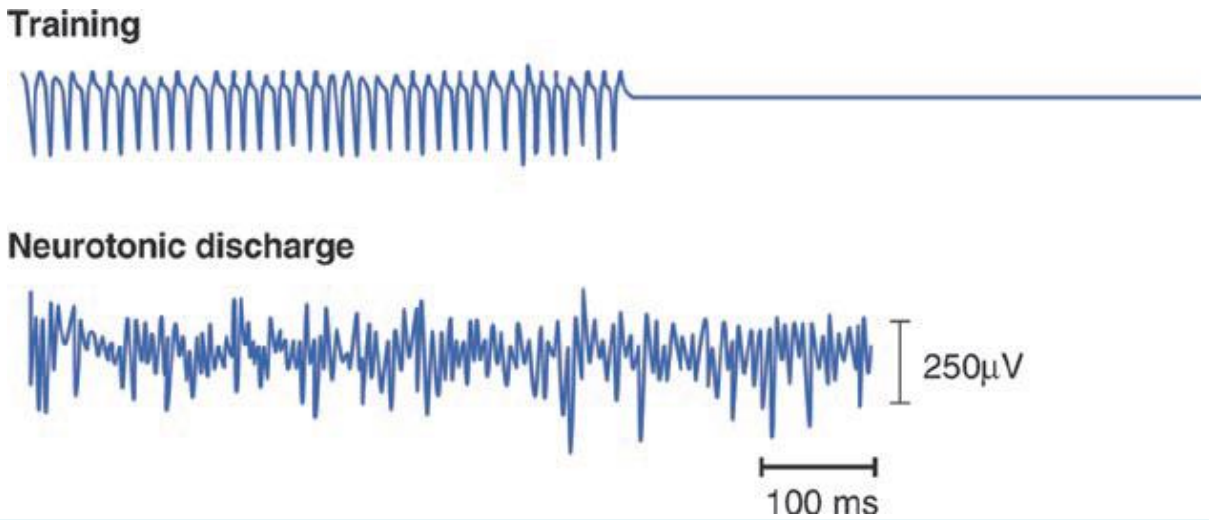
Free running (Spontaneous) EMG

Train

- **Sustained periodic** firing of one or more motor units
- Lasting from **seconds to minutes**
  - The length of time: the **degree of nerve irritation**
  - **> 10 seconds ➡ Postoperative deficits**

- **Variable**
- **Repetitive** discharges

- Nerve **Traction** or **Pressure**
- **Direct mechanical trauma**
- **Irrigation**



Free running (Spontaneous) EMG

A Train

Sinusoidal Pattern

Short duration

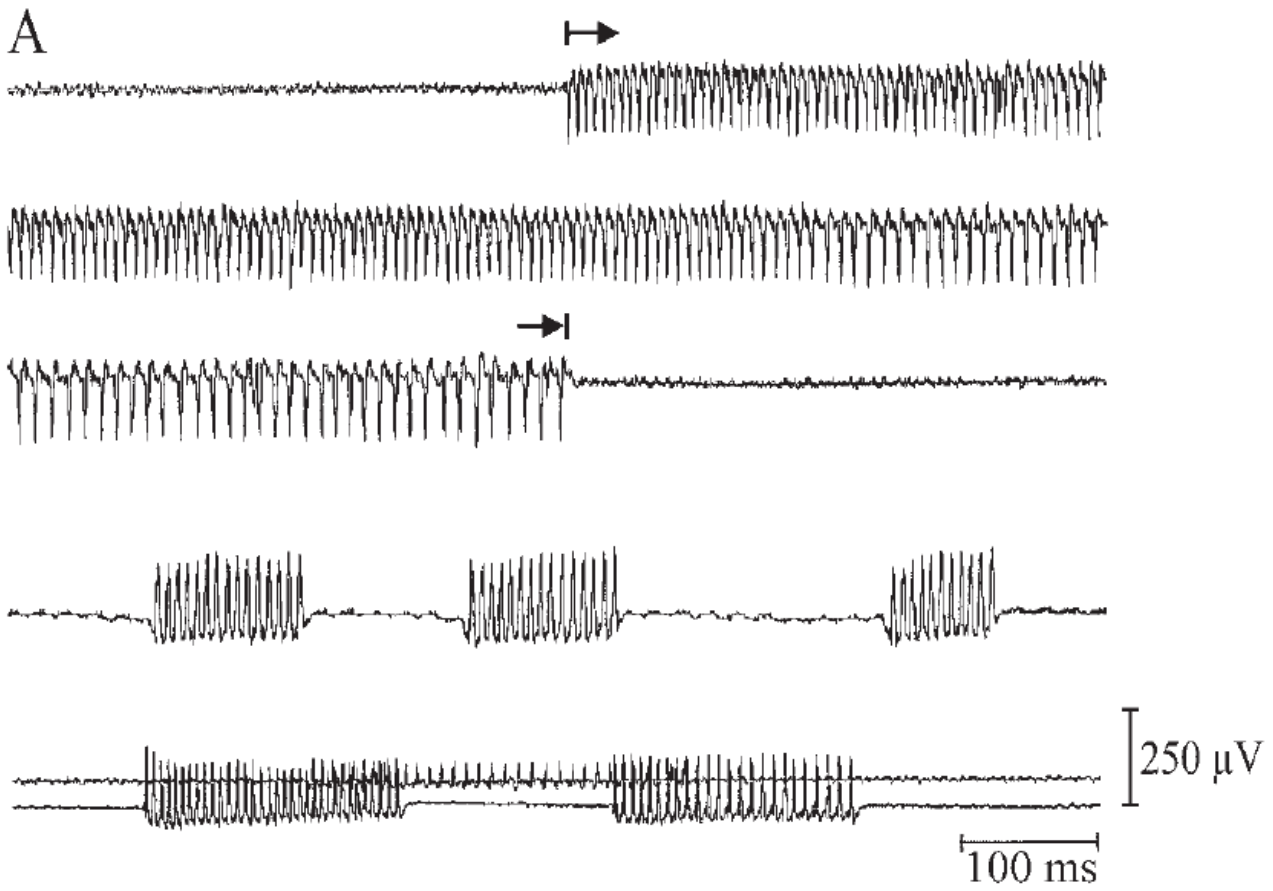
with a **more or less rhythmic sequence**

It always started **suddenly**

High Frequency (60 – 210 Hz)

Amplitude (100 – 200 µV)

Duration (milliseconds - several seconds)



Free running (Spontaneous) EMG

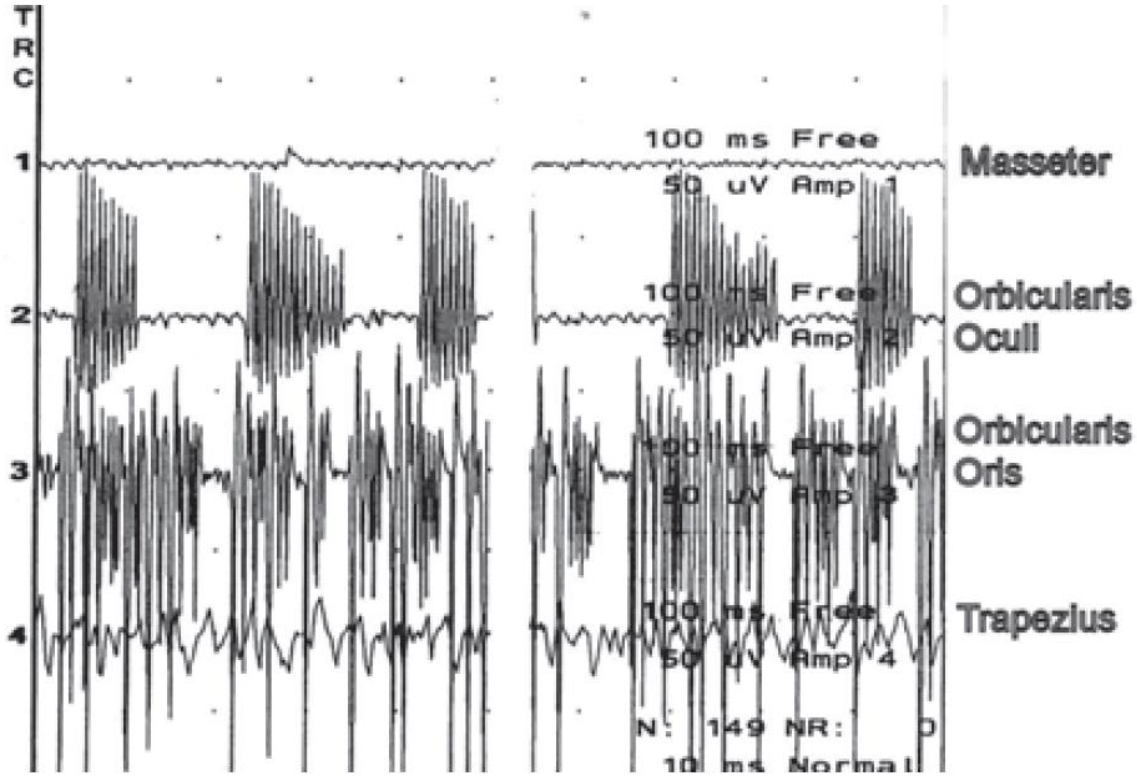
A Train

Additional postoperative motor deficits

In Facial nerve,

- Sensitivity 86 %
- Specificity 89 %

Complex repetitive discharges



Free running (Spontaneous) EMG

B Train

Regular or **Irregular** sequence

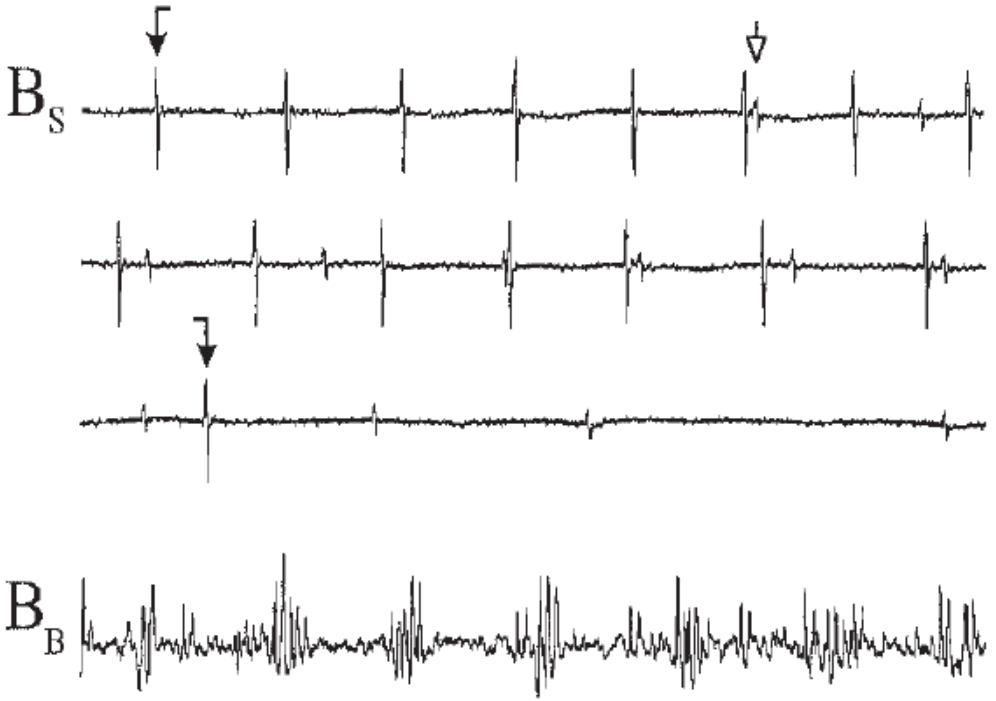
of single components

maximum intervals of 500 msec

Several minutes - hours

Myokymic Discharges

Pathophysiological mechanism is not clear



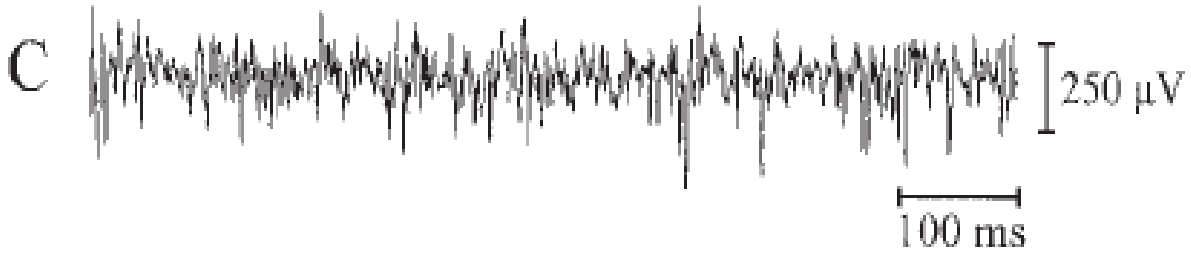
Free running (Spontaneous) EMG

C Train

Continuous irregular EMG activity

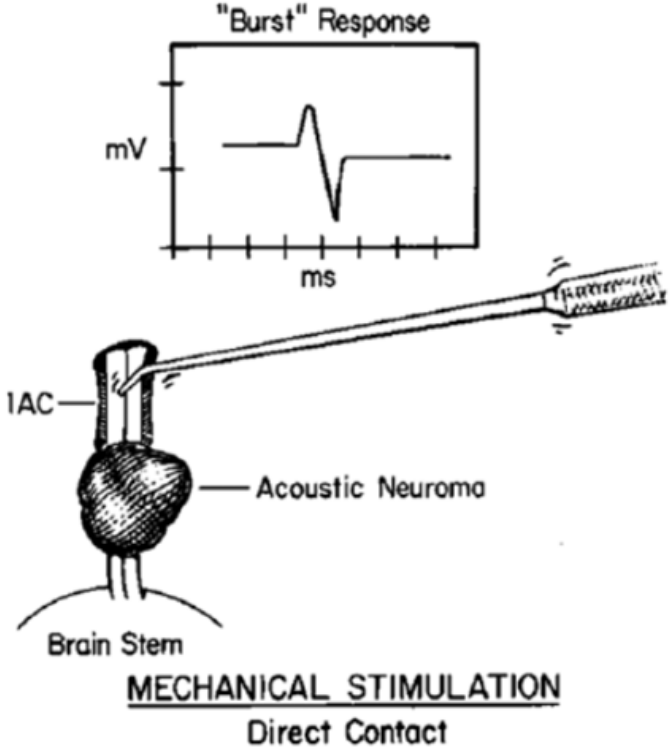
Numerous **overlapping** components

20 to more than 5000 μV

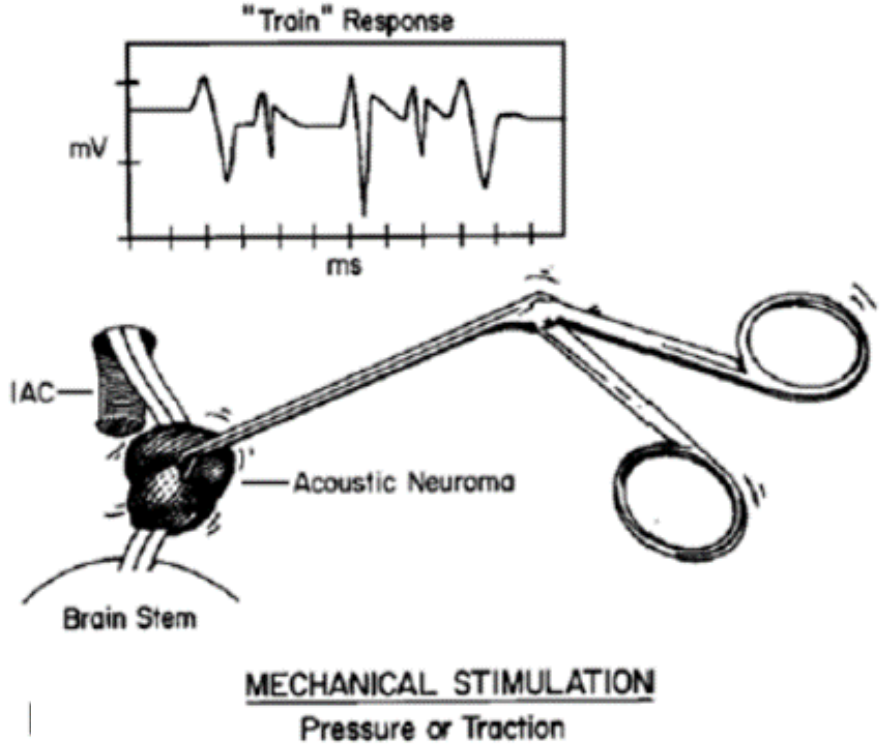


Free running (Spontaneous) EMG

Bursts



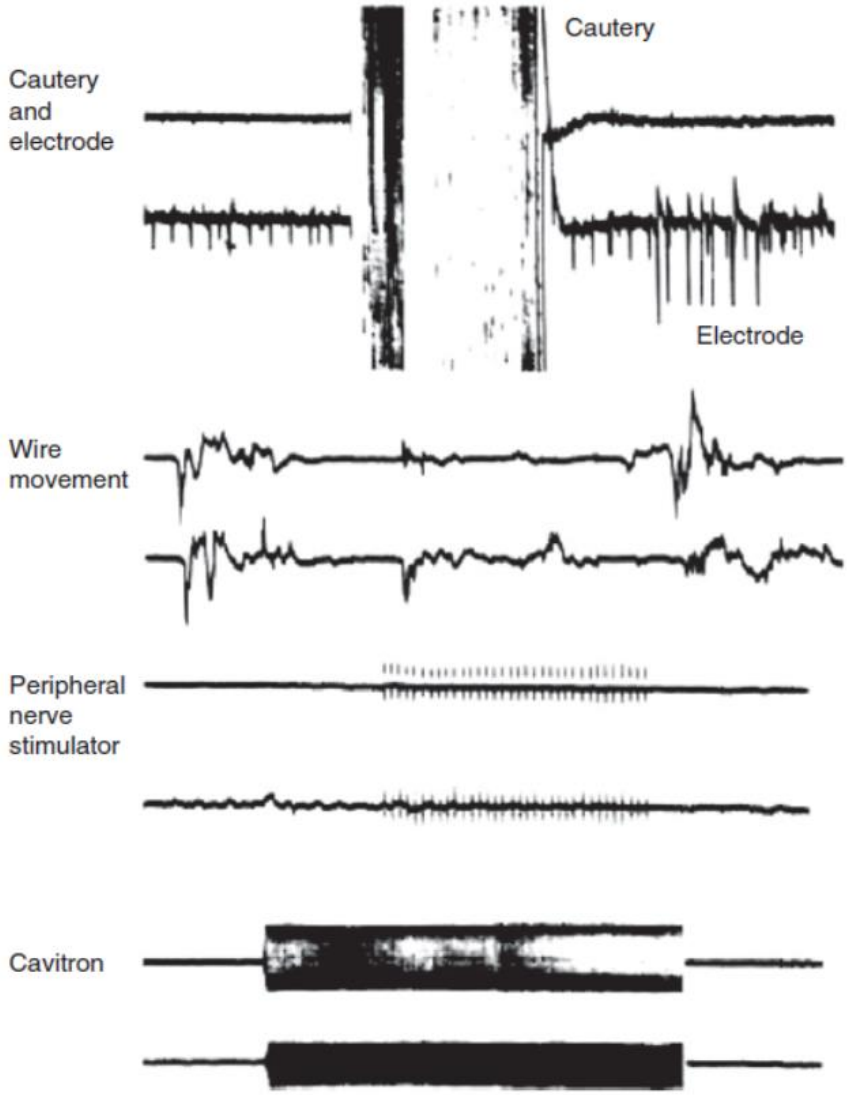
Train



Free running (Spontaneous) EMG

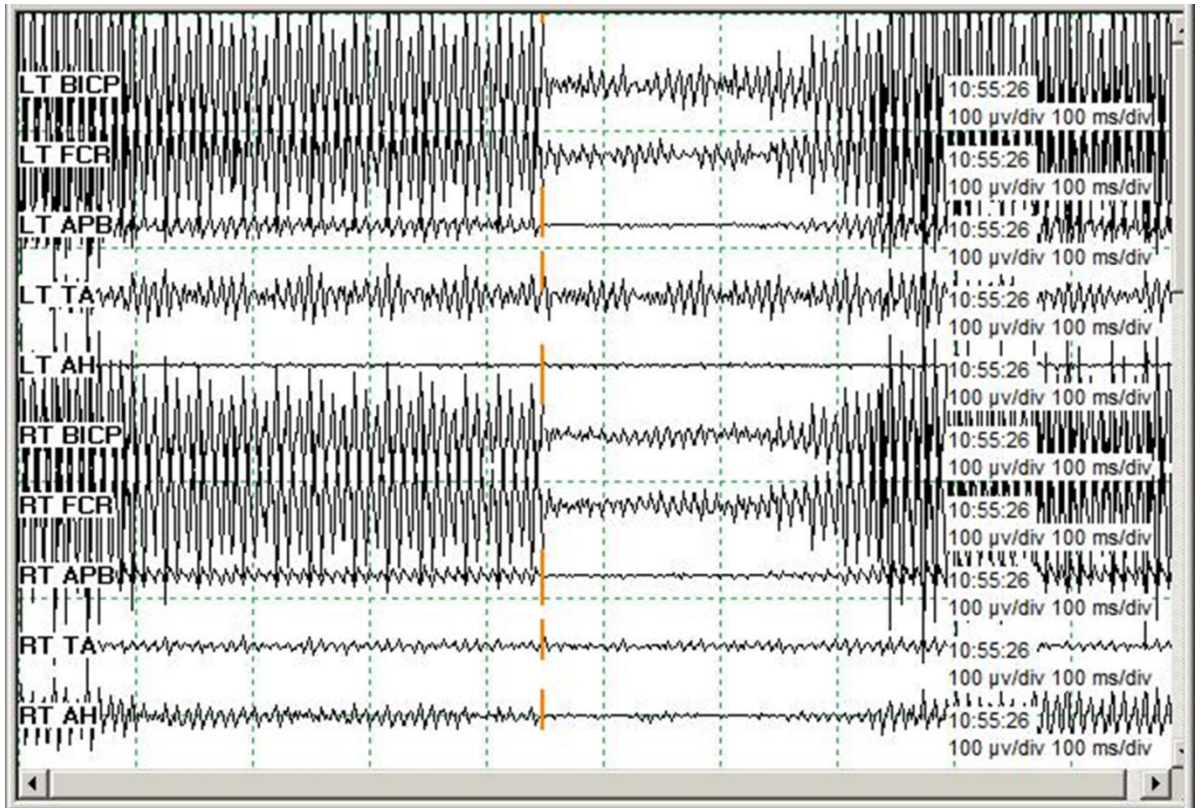
Artifactual activity

- **Cautery**
- Peripheral nerve stimulator (SEP)
- Others



Free running (Spontaneous) EMG

Artifactual activity



Free running (Spontaneous) EMG

Artifactual activity

Free running (Spontaneous) EMG

Advantages	Disadvantages
Simple	**False-positive** or **False negative** results
Real time monitoring	- Absent following serious nerve injury
Immediate feedback	- Including **sharp nerve dissection**
	High sensitivity & relatively **Low specificity**
	No warning criteria

Stimulated (Triggered) EMG

Stimulated EMG is used for primary reasons

Identify a nerve or nerve root of interest

- Anatomical variation of the motor nerves

Assess the functional integrity of a nerve or nerve root

Assess the placement of pedicle screws

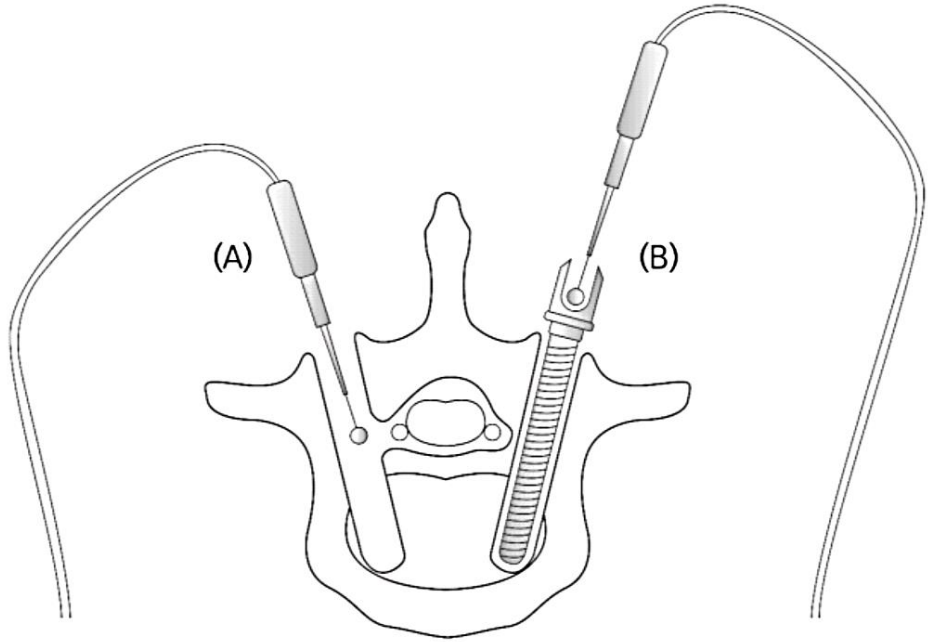
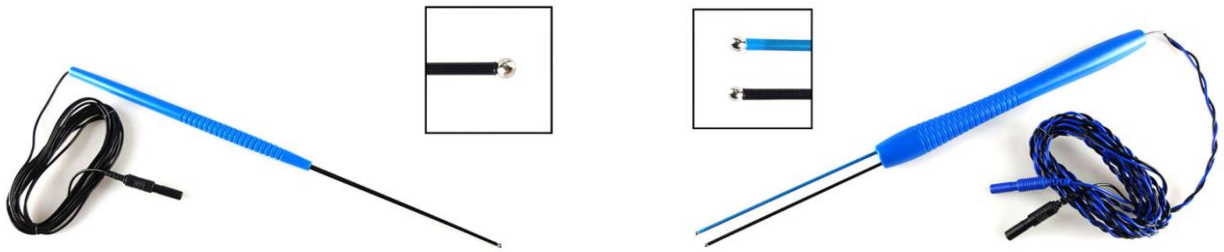


Fig. 1. Indirect nerve root stimulation. (A) Insertion tract stimulation, (B) Pedicle screw stimulation.

Stimulated (Triggered) EMG

Identifying nerves and nerve roots

- **Direct Electrical Stimulation**
  - A branch of a cranial nerve
  - the level of a spinal nerve root



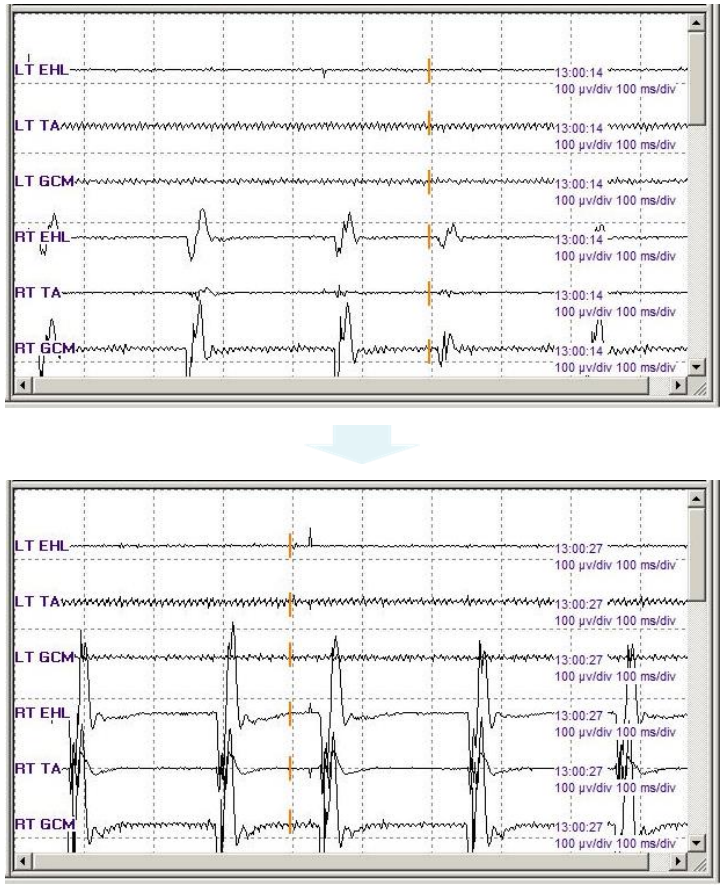
- Stimulation
  - Hand-held probe, insulated to the tip
  - Square wave pulses
  - Pulse width of 50-100 *μsec*
  - 2 – 3.5 Hz

Stimulated (Triggered) EMG

Identifying nerves and nerve roots

the locus of stimulation approaches the nerve

- CMAP
  - Lower the threshold
  - **Shorter** latency
  - **Higher** amplitude
  - **Less** spread of excitation to near by nerves



Stimulated (Triggered) EMG

Identifying nerves and nerve roots

- Beginning at 0.00 mA, the current is carefully increased until a **CMAP is recorded with minimal spread to other nerves/muscles.**

- **Stimulation Intensity**
  - **Healthy nerve < 2 mA**
  - **Pathologic nerve & nerve roots** (Previously injured, chronically compressed, etc.) **≥ 3mA**
- **Latency**
  - Cranial nerve: 2 – 10 ms
  - Spinal nerve root: 15 – 25 ms

Stimulated (Triggered) EMG

Stimulation Threshold ≤ 1.0 mA

↓

Neural Proximity

↓

The surgeon should dissect with caution

Stimulated (Triggered) EMG

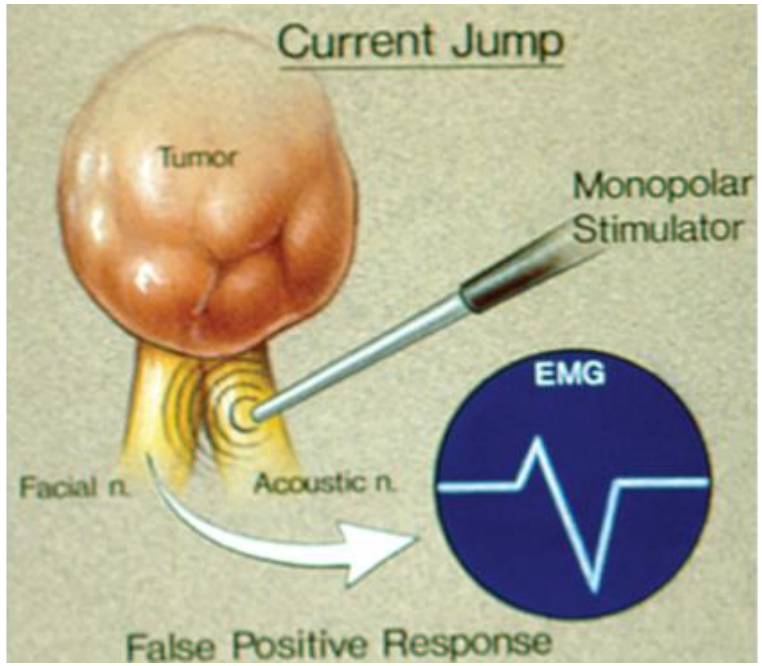
Identifying nerves and nerve roots

False Positive errors (Current Jump)

volume conduction of current through **nearby tissues**

CMAP recorded from **unexpected location** due to **unintended depolarization of a different nerve**

- Using **bipolar probe**
- **lowest monopolar current** levels possible to obtain a response



(Kircher & Kartush, 2012)

Stimulated (Triggered) EMG

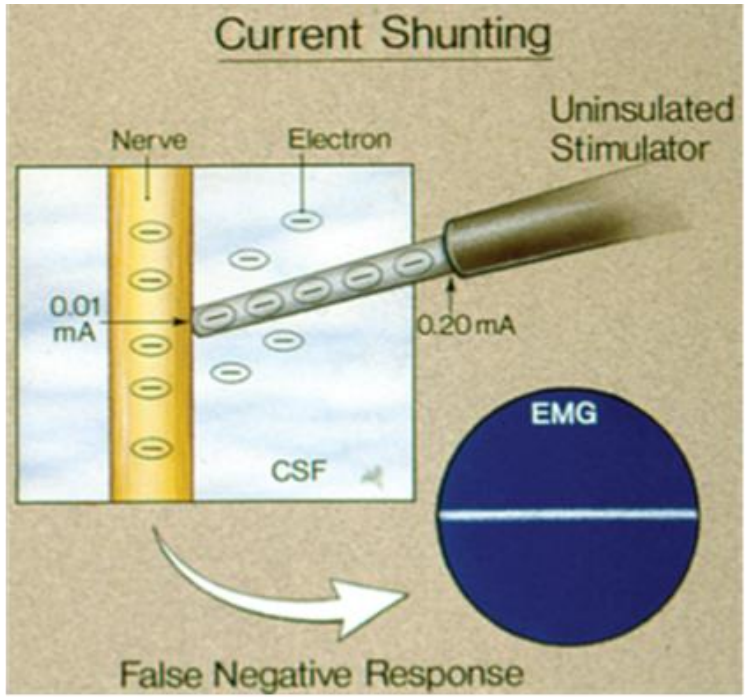
Identifying nerves and nerve roots

False Negative errors (Current Shunting)

The presence of **CSF** and **Blood** in the field

no CMAP recorded because **current bypasses** the target nerve **and** flow directly to the return electrode

- **Electrical insulation** along the stimulator's shaft
- Applying **suction** during stimulation



(Kircher & Kartush, 2012)

Stimulated (Triggered) EMG

Assessing the Functional Integrity of a Nerve or Nerve Root

Direct Electrical Stimulation

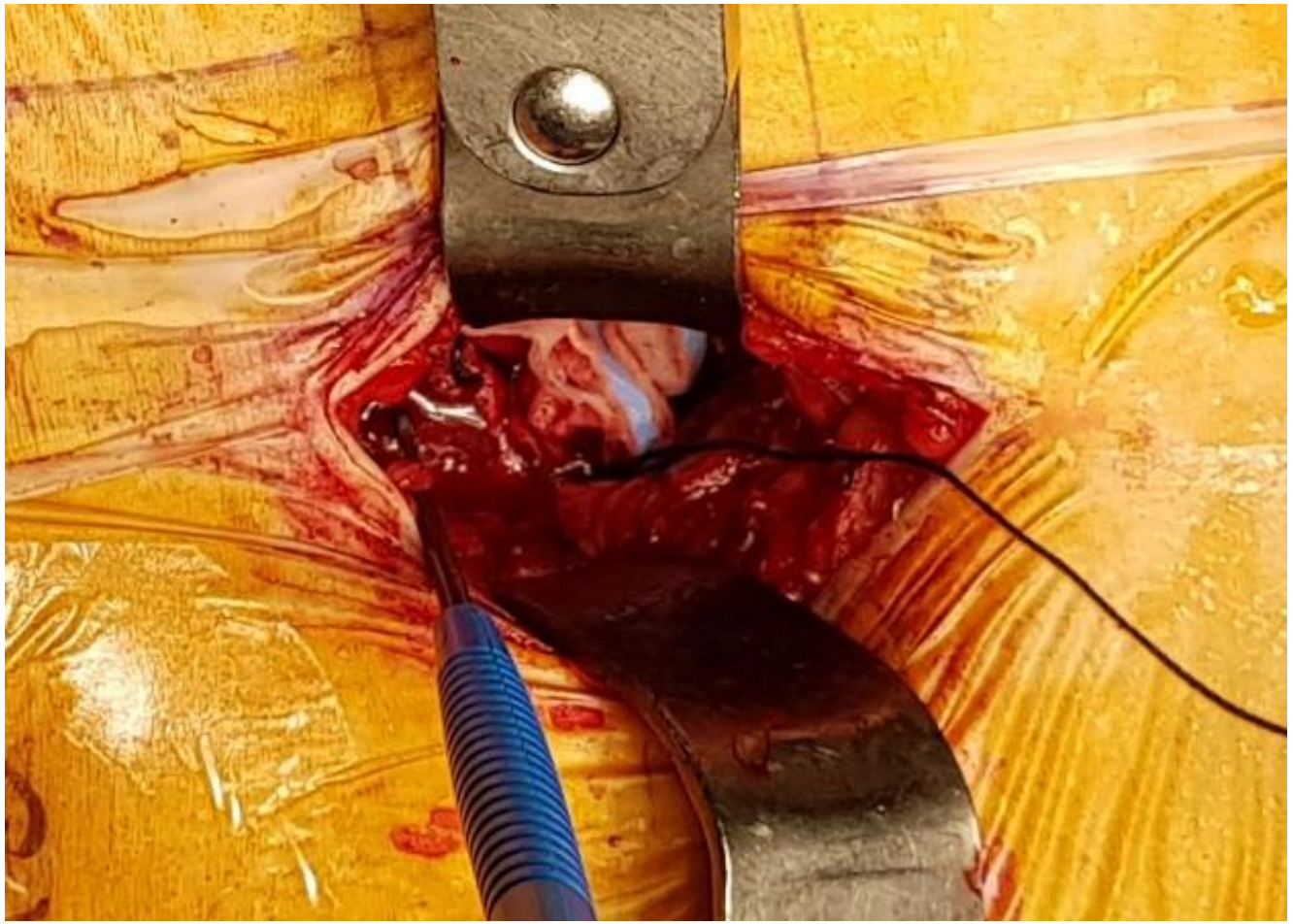
Stimulation Threshold

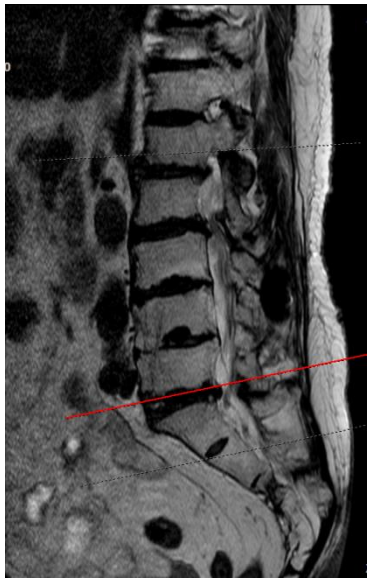
- **Healthy nerves: < 2 mA** (often < 1mA)
- **Pathologic nerves: Higher** threshold

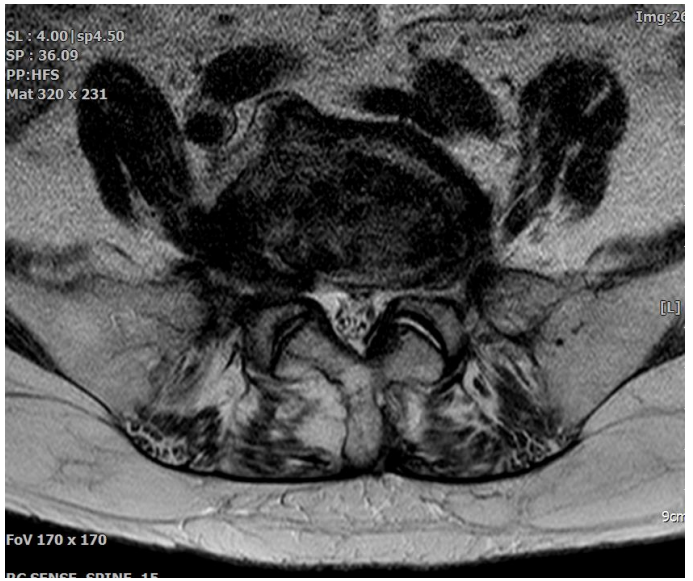
Structure	Stimulus threshold (mA)
Normal nerve root	(0.2–5.7)
Chronically compressed nerve root	6.3–20

(Maguire et al., 1995)

Direct nerve root stimulation





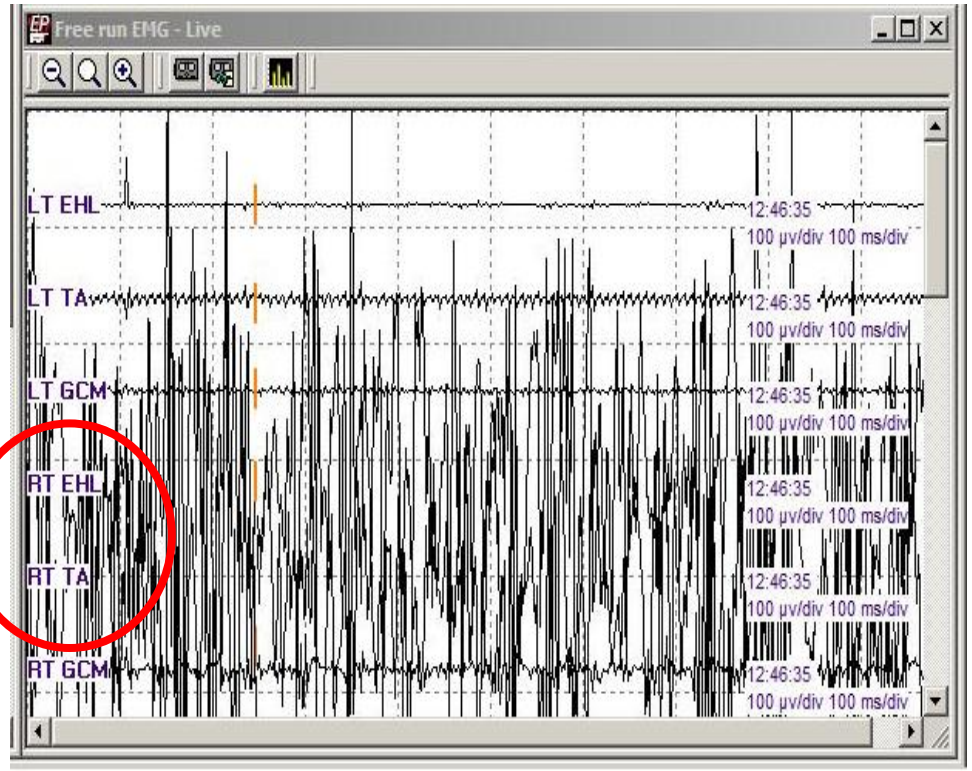


Bilateral L5/S1 Extraforaminal lesion

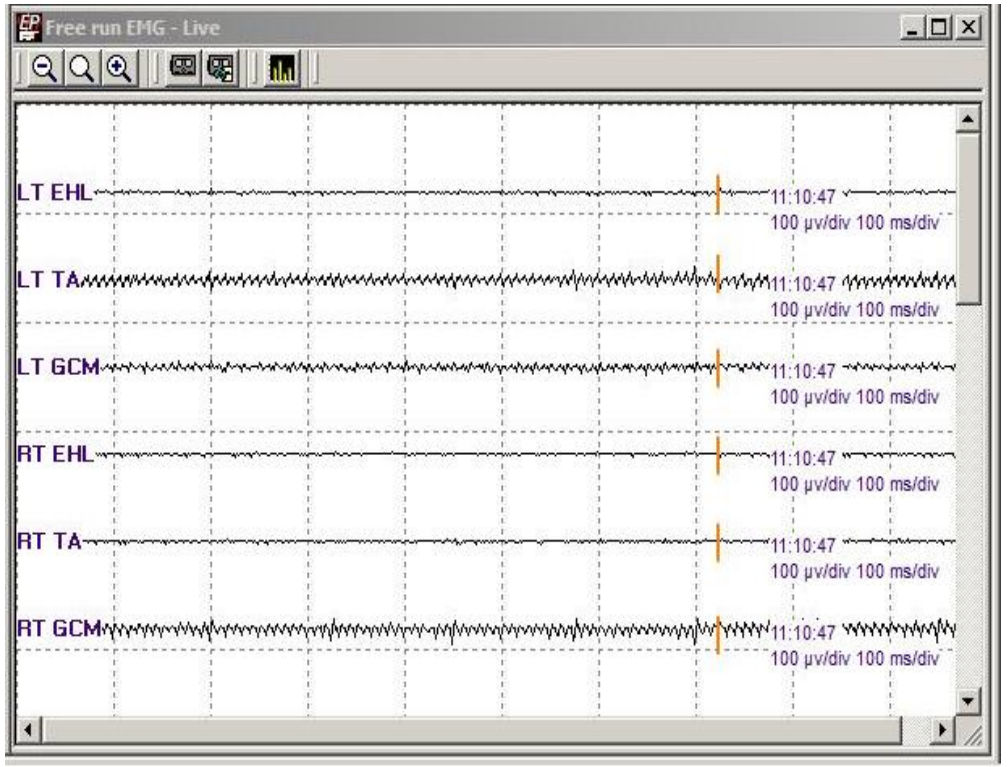
Direct spinal root stimulation

Electrodiagnostic Study: Bilateral chronic L5 radiculopathy

Rt. L5 root (6 mA)

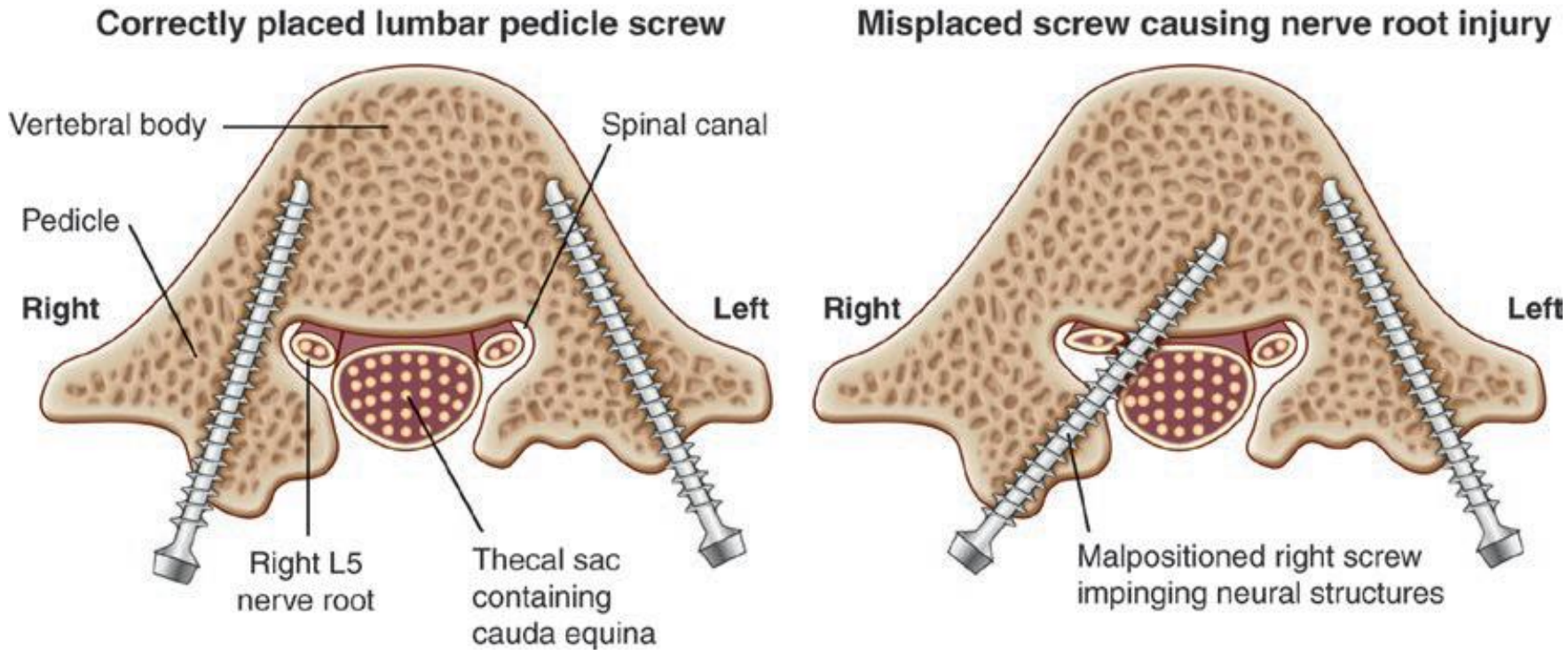


Lt. L5 root (9 mA)



Stimulated (Triggered) EMG

Stimulating Pedicle Screws



Stimulated (Triggered) EMG

Stimulating Pedicle Screws

Bone

- **Electrical insulator**
- **Limit** the amount of **current transfer** between **stimulated screw** and the **neural element**

Breach in the pedicle wall

Low resistance conduit of electricity (screw to nerve root)

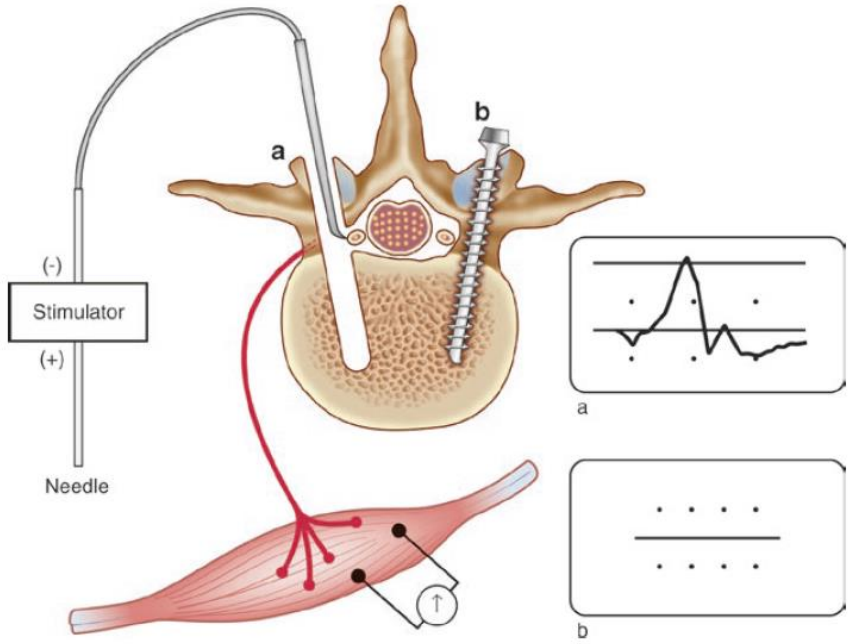
Recordable as a CMAP in the myotome of that nerve root

Stimulated (Triggered) EMG

Stimulating Pedicle Screws

- If a **large amount of current** is required for activation of the nerve roots, it is a reasonable assumption that the **bone is contact.**

- **Lower stimulation thresholds** indicate a **potential breach**



Stimulated (Triggered) EMG

Stimulating Pedicle Screws

TABLE 2.3 Threshold Values Indicating the Likelihood of Pedicle Screw Malpositioning

	Perforation probable	Perforation possible	Perforation unlikely
Hole	<5 mA	5–7 mA	>7 mA
Screw	<7 mA	7–10 mA	>10 mA

(Husain, 2008)

Stimulated (Triggered) EMG

Stimulating Pedicle Screws

1. Stimulation starts at 0 mA
2. Increments of **0.5–1 mA** until a **response is seen**

- Stimulation of the **pedicle screw**
- Stimulation of the pilot **hole** prior to screw placement

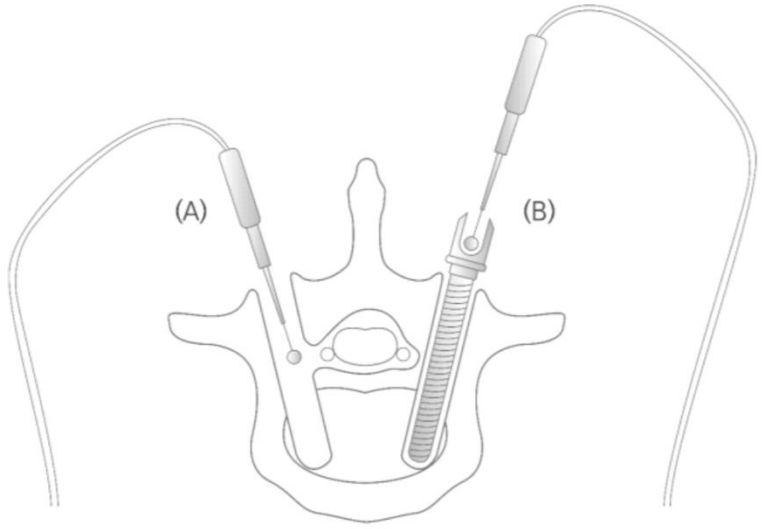
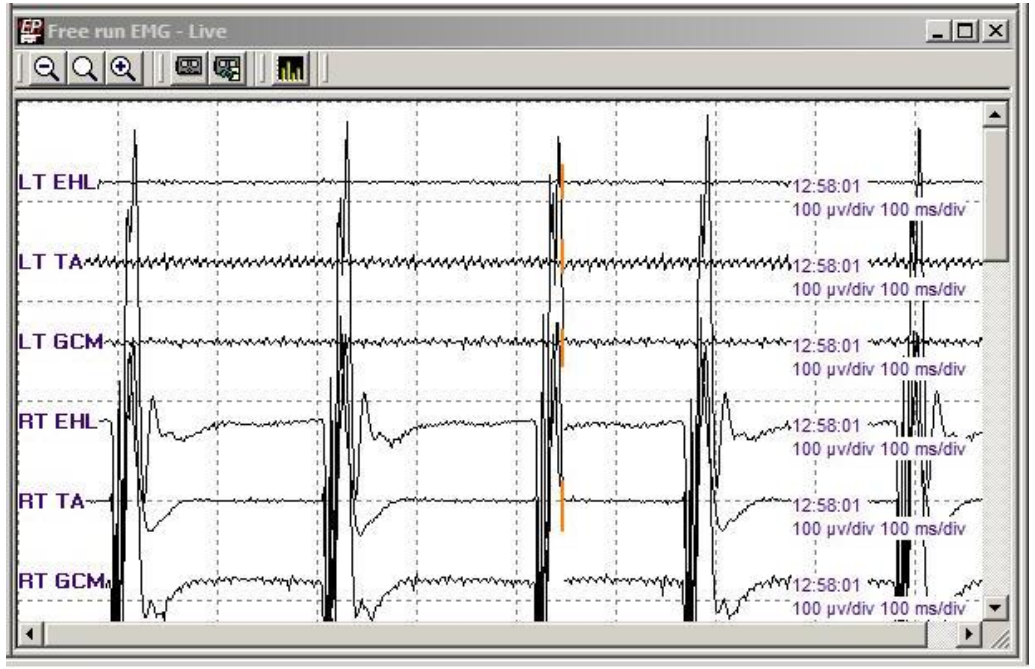


Fig. 1. Indirect nerve root stimulation. (A) Insertion tract stimulation, (B) Pedicle screw stimulation.

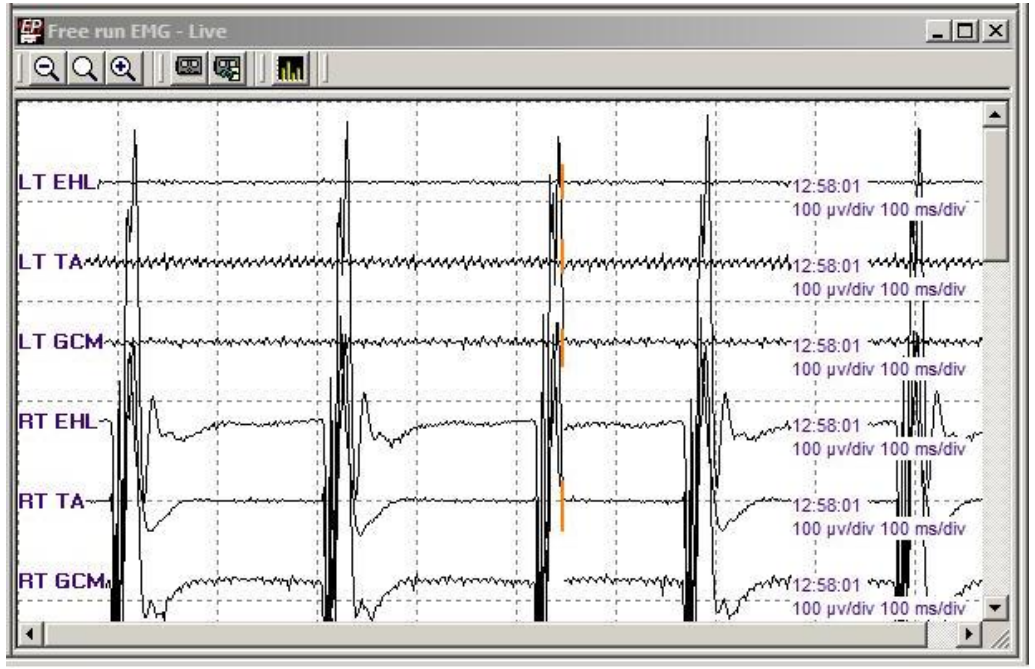
Stimulated (Triggered) EMG

Pedicle stimulation (6 mA)

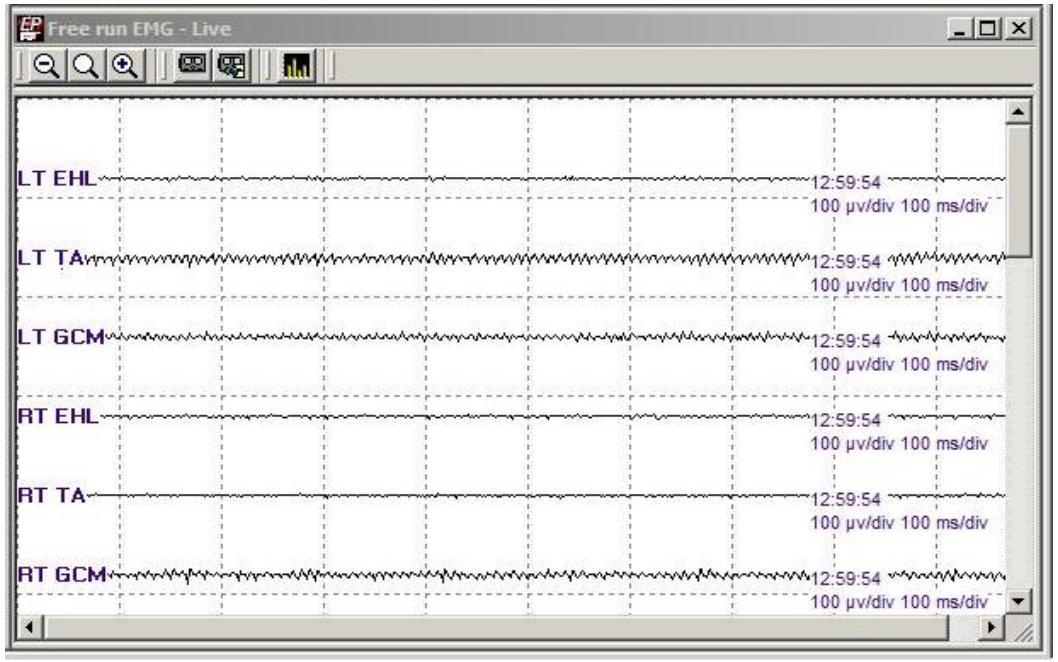


Stimulated (Triggered) EMG

Pedicle stimulation (6 mA)



Pedicle stimulation (10 mA)



	Monitoring	Advantages	Limitations	Alarm criteria	Anaesthetic requirements	Sensitivity	Specificity
SSEP	Functional integrity of sensory pathways	Continuous monitoring: firm warning criteria More recording sites, more reliable result. Generally better resistance of anaesthetics than MEP	Signal averaging results in time delay: injury can be irreversible before detection Influence of halogenated and nitrous-oxide-based agents	Latency increase > 10%, signal decrease > 50%	Intravenous anaesthesia, eventually dexmedetomidine	25–92%	96–100%
MEP	Functional integrity of motor pathways	Real-time monitoring, instant, no averaging Reliable even after posterior myelotomy More sensitive to ischemia Less sensitive to electrical noise	Requires total intravenous anaesthesia without neuromuscular blockade Movements Contraindicated in seizures and pace makers Wide warning criteria	Signal decrease > 50–75%	Total intravenous anaesthesia, no halogenated agents or neuromuscular blockade	75–100%	84–100%
EMG	Functional integrity of peripheral nerves	Constant feedback, Combined with SSEP improved specificity, Easy performance and interpretation	High rate of false positives Very sensitive on temp. changes and cautery Rriggered EMG: only insight in pedicle integrity	No firm alarm criteria	Avoidance of neuromuscular blockade	Free-running: 100% Triggered: 99.5%	Free-running: about 23% Triggered: low
Multimodal IONM	All of the above	Both modalities together improve sensitivity and specificity: most reliable	Highly trained personnel Technical requirements Cost	Avoidance of each of the above-mentioned limitations with adjusted anaesthetic protocols will provide sensitivity of 100% and specificity of 84–100%.			

(Biscevic, Sehic, & Krupic, 2020)

Multimodal IONM

TABLE 1. Statistical analysis[a]

	SEP	TCE-MEP	EMG	Combined TCE-MEP and EMG
No. of monitorable cases	10	14	14	14
% monitorable	71.4%[b]	100%	100%	100%
Positive predictive value	1.0	1.0	0.875	0.889
Negative predictive value	0.833	0.75	0.833	1.0
Sensitivity	80%	75%	87.5%	100%
Specificity	100%	100%	83.33%	83.33%

(Skinner et al., 2005)

Multimodal IONM

Table 3 Sensitivity and specificity of intraoperative monitoring

Study name	Year	No. of patients	IOM change	MEP change	SSEP change	Sensitivity and specificity (SSEP)	Sensitivity and specificity (MEP)	No. of new neurological deficits
Plata Bello et al.	2015	75	5 (6.6%)	5	2	(40%; 100%)	(100%; 100%)	–
Appel et al.	2017	381	9 (2.3%)	7	2	(22%; 100%)	(78%; 100%)	2
Hilibrand et al.	2004	427	15 (3.5%)	12	3	(25%; 100%)	(100%; 100%)	2
Sakaki et al.	2012	357	196 (55%)	196	–	–	(100%; 83.2%)	0
Oya et al.	2017	135	12 (8.9%)	12	0	–	(100%; 98.4%)	–

IOM intraoperative monitoring, *SSEP* somatosensory evoked potential, *MEP* motor evoked potential

(Di Martino et al., 2019)

Multimodal IONM

- The base hypothesis advocated in this study is that the combination of SSEP and MEP might be more sensitiveand specific than IONM.
- On the basis of available evidence, we support use of **MIOM in decompression cervical spine surgery in patients affected by degenerative spinal stenosis**, since it is associated with high specificity and sensitivity for detection of intraoperative neural damage.

Consideration of IONM in spine surgery

- Preoperative assessment
- Intraoperative monitoring
  - When
  - What
  - How

Preoperative assessment

- Past Medical & Surgical History
  - Pacemaker c defibrillator
- **Radiologic images**
- **Electrodiagnostic study c Evoked Potentials**
- Anesthetic Plan
- **Surgical Plan & Procedure**

Potential Risk of Surgery

IONM Plan

- **Selection of modality**
- **Selection of Proper muscles**

IONM modalities

TcMEP
Hand (APB)
Foot (AH)

SEP
Median nerve
Posterior Tibial nerve

Free run EMG
Hand (APB)
Foot (AH)

Selection of Proper muscles

Spinal root myotomes

C1 – None

C2 – Sternocleidomastoid

C3 – Trapezius, sternocleidomastoid

C4 – Trapezius, levator scapulae

C5 – Deltoid, biceps

C6 –Biceps, triceps, brachioradialis, pronator teres, flexor carpi radialis (FCR)

C7 –Triceps, pronator teres, FCR, forearm extensors

C8 –Triceps, ulnar forearm muscles, all hand intrinsic muscles (incl. abductor pollicis brevis, first dorsal interosseous, adductor digiti minimi)

T1 –Hand intrinsic muscles, flexor carpi ulnaris

T2,T3, T4, T5, T6 – Intercostal muscles, paraspinal muscles

T6,T7, T8 – Upper rectus abdominis, paraspinal muscles, intercostal muscles

T8,T9, T10 – Middle rectus abdominis, paraspinal muscles, intercostal muscles

T10, T11, T12 – Lower rectus abdominis, paraspinal muscles, intercostal muscles

L1 –Quadratus lumborum, paraspinals, cremaster ± iliopsoas ± internal oblique

L2 –Iliopsoas, adductor longus, quadriceps, adductor magnus

L3 –Quadriceps, adductor longus, adductor magnus, iliopsoas

L4 –Quadriceps, tibialis anterior, adductor longus, adductor magnus, iliopsoas

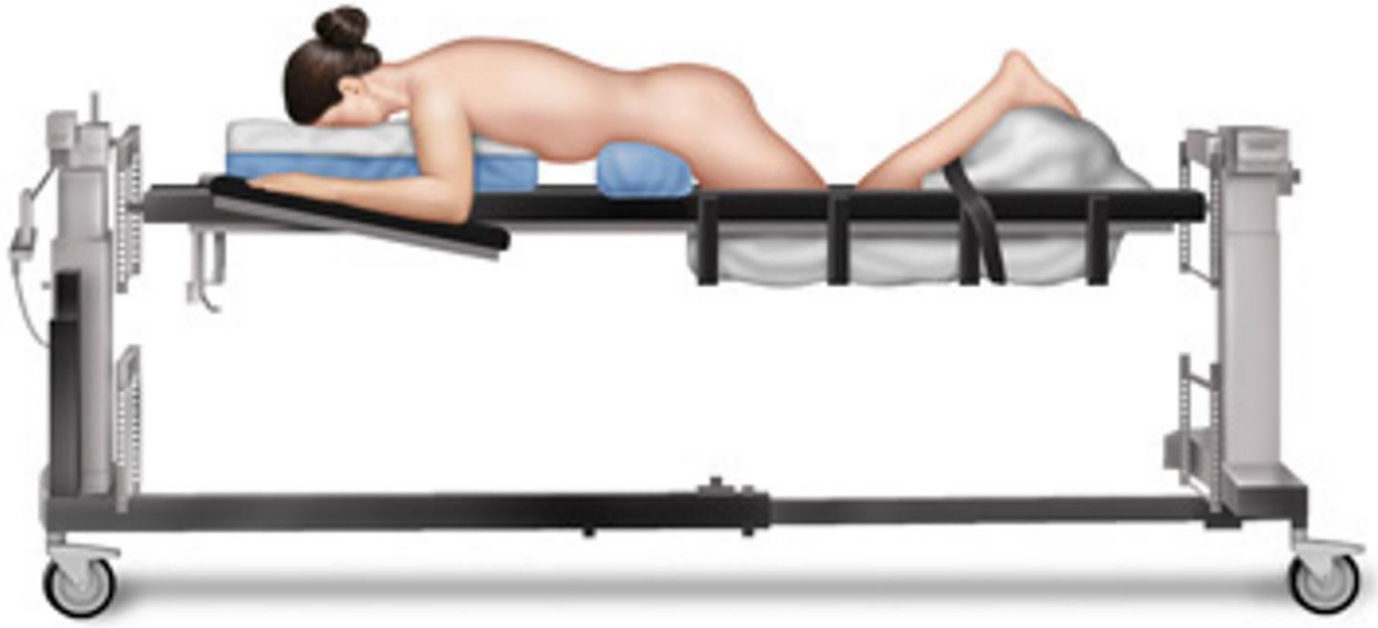
L5 –Tibialis anterior, peroneus longus, adductor magnus

S1 – Gastrocnemius, abductor hallucis

S2 – Gastrocnemius, abductor hallucis

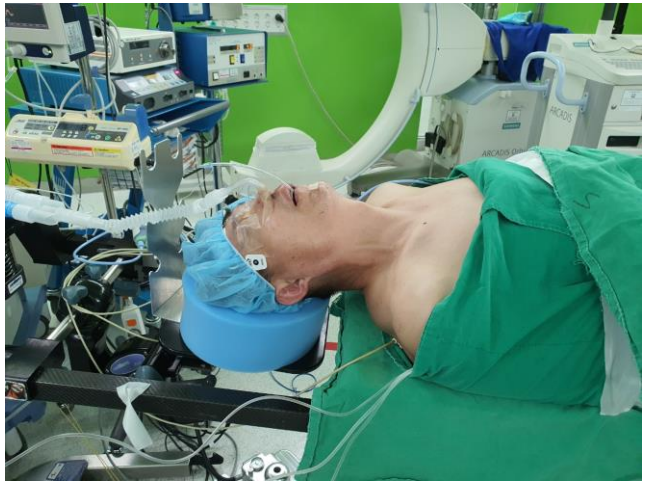
S2–S5 – Anal sphincter, urethral sphincter

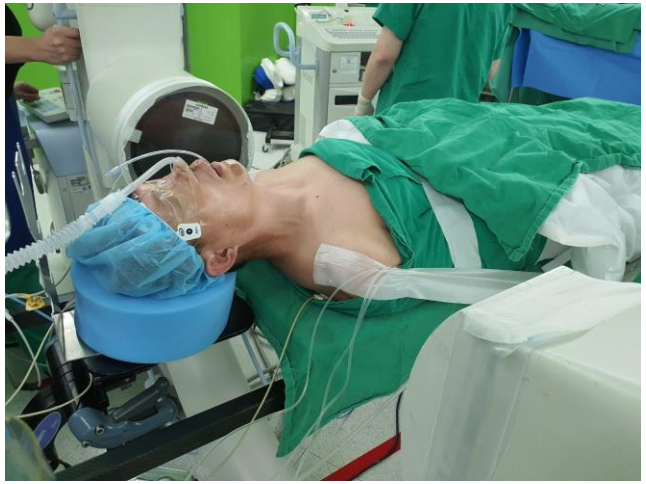
IONM - Positioning

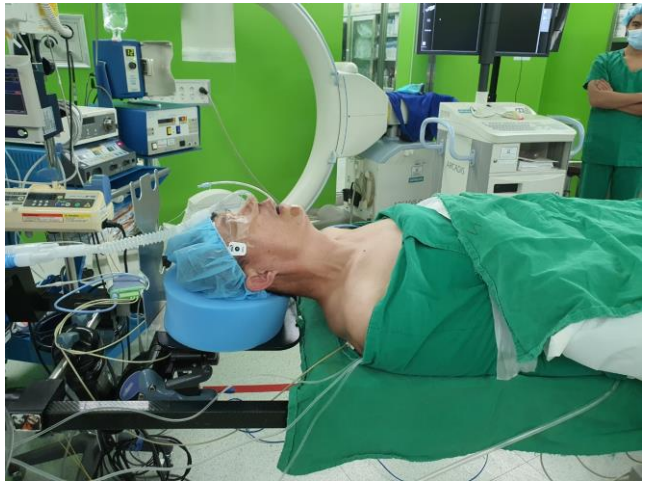


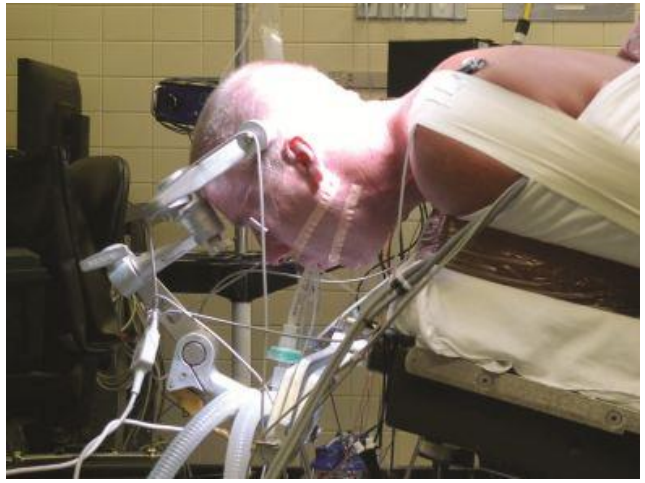
- Risk
  - **Spinal cord**
  - **Nerve root**
  - Brachial plexus
  - Femoral nerve injury

IONM – Positioning









IONM - Positioning

Table 3
Features of the five patients who presented IONM alerts during positioning.

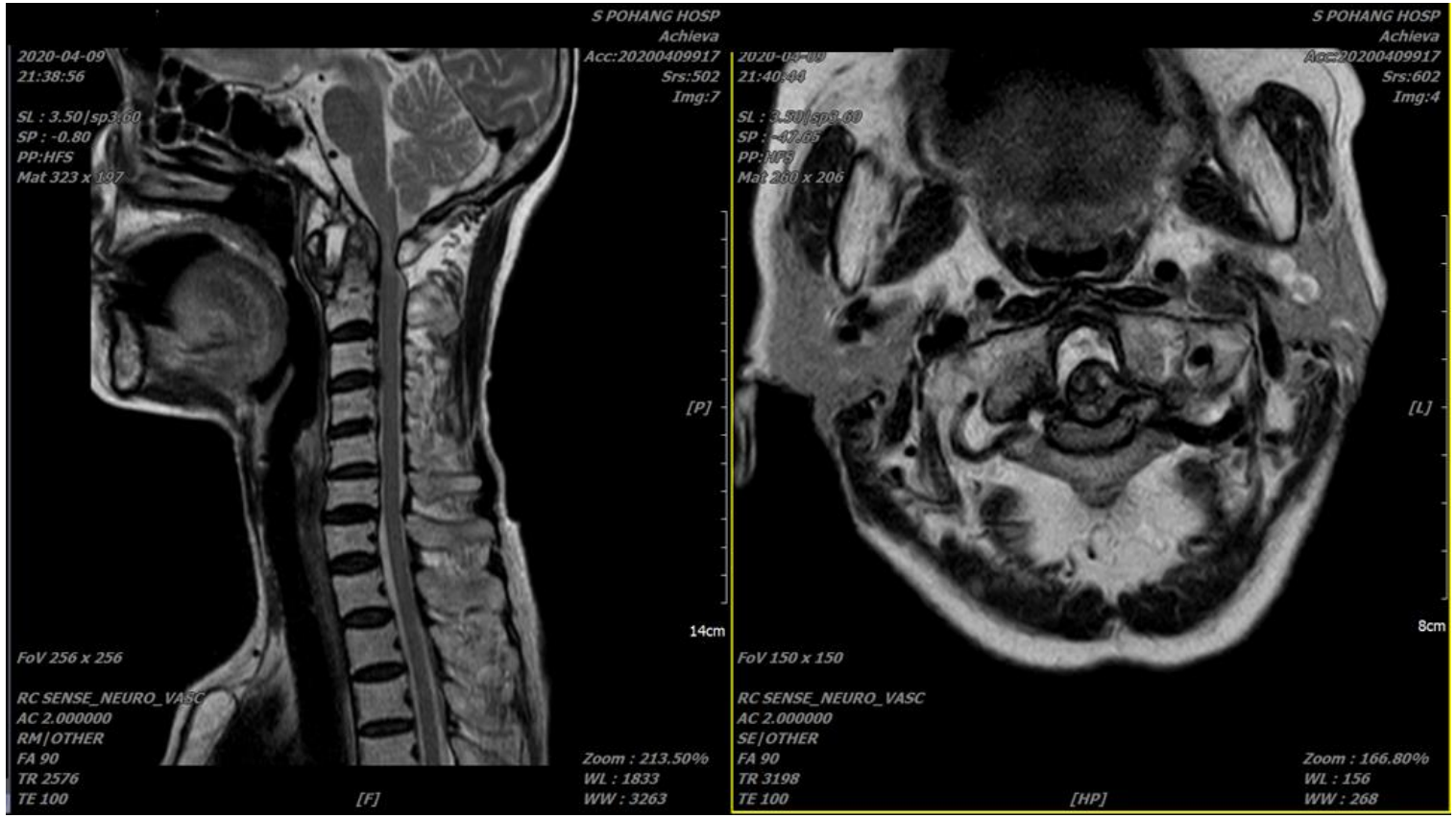
	Gender	Age	Diagnosis	Approach	Warning	Outcome
Patient 1	Male	50	Degenerative myelopathy	Anterior	Loss of MEPs in both AH and TA. Loss of cortical SEPs	Recovery after neck reposition. No deficit
Patient 2	Male	77	Degenerative myelopathy	Posterior	Loss of right TA and AH MEPs	Recovery after repositioning of the arms. No deficit
Patient 3	Male	50	Disc herniation	Anterior	Loss of both FDI, right TA and right AH. Loss of cortical SEPs	No recovery. Postsurgical deficit
Patient 4	Male	69	Degenerative myelopathy	Posterior	Loss of right FDI and both TA	Recovery after neck reposition. No deficit
Patient 5	Male	47	C5-C6 luxation	Posterior	Loss of MEPs in both AH and TA	Recovery after neck reposition. No deficit

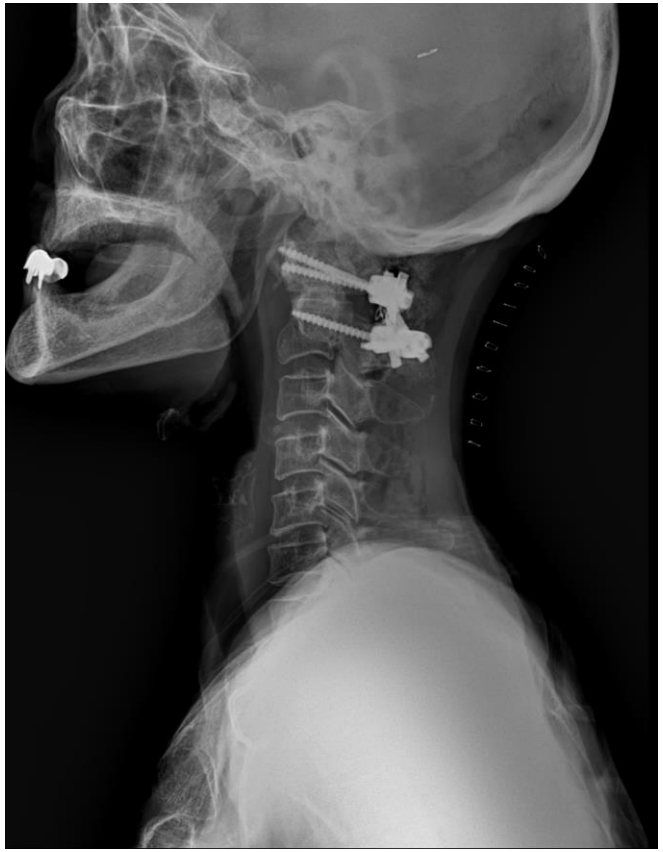
AH: Abducens Hallucis; FDI: First Dorsal Interosseus; TA: Tibial Anterior.

(Plata Bello et al., 2015)

IONM – Positioning

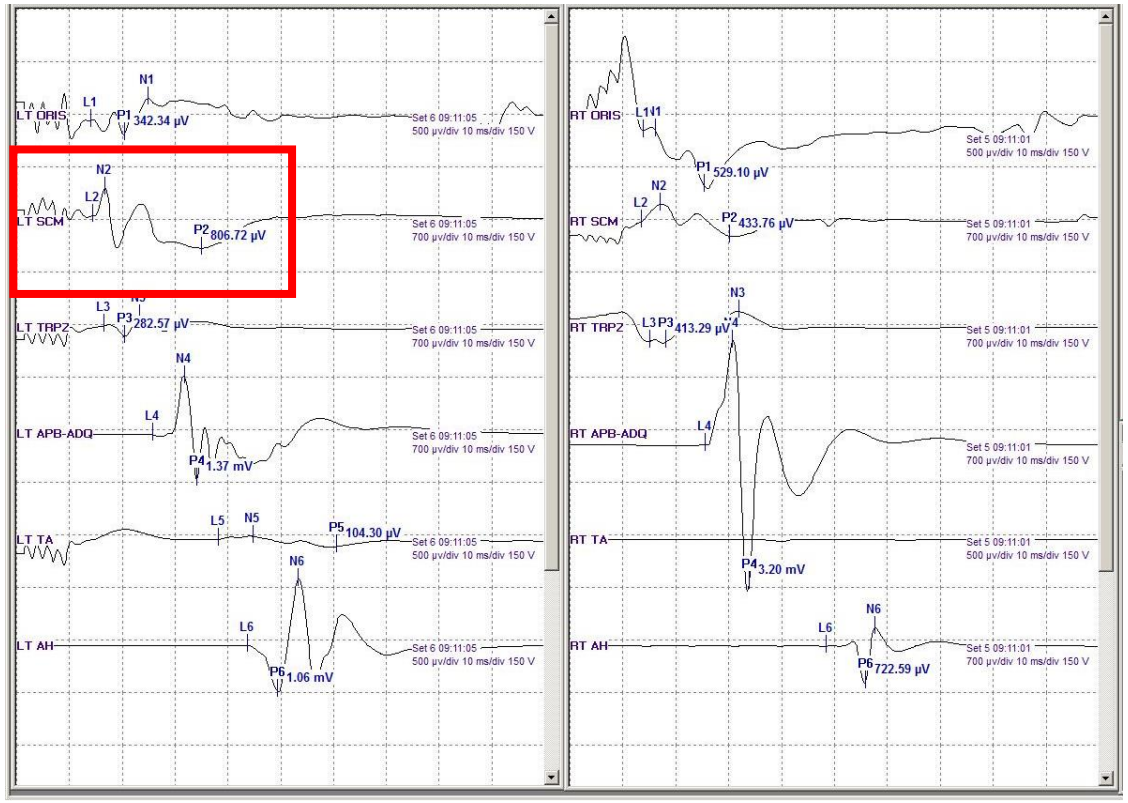
Cervical cord lesion d/t C1/2 instability



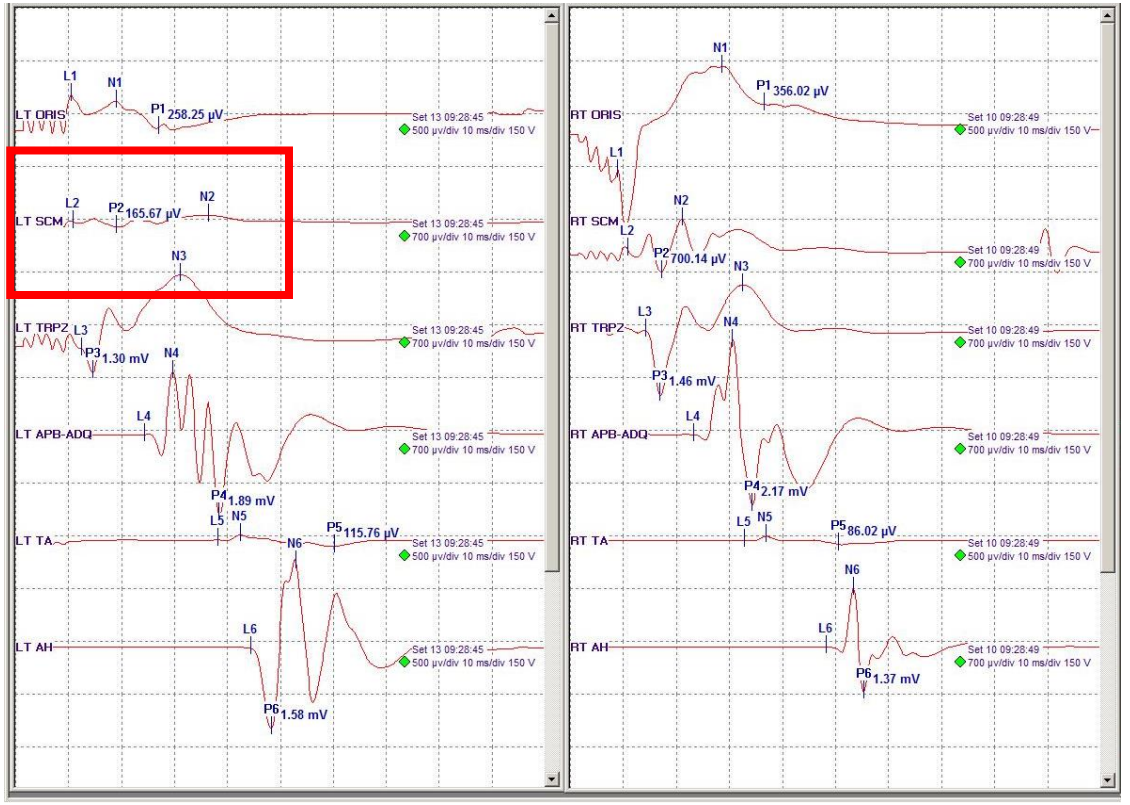


IONM – Positioning

Cervical cord lesion d/t C1/2 instability



Supine



Prone

IONM - Opertaion

Positioning

Main Procedure

Laminectomy & Corpectomy

Lift of lamina

Cage placement

Correction of deformity

Direct Trauma

Bleeding

Closing time

Table 7. Intraoperative Neuromonitoring Profiles of the Cases and Postoperative Motor Deficit with Intraoperative Neurophysiologic Monitoring Changes During Cervical Open Door Laminoplasty

Patient Number	Diagnosis	MCL	OR Area (%)	Surgical Method	Time of IONM Change	Open Side of Laminas	MEP Change		SSEP Change		Recovery of IONM Change	Postoperative Motor Deficit
							Amplitude Decrease (50%)	Complete Loss	Amplitude Decrease (50%)	Complete Loss		
1	OPLL	C5-6	43.4	B	After lift of all laminas	Left	Left deltoid				Full recovery	No deficit
2	OPLL	C3-4	48.8	A	After C3 laminectomy	Left	Right deltoid, left APB	Right APB, right TA			Partial recovery	No deficit
3	OPLL	C3-4	50.9	A	After C3 laminectomy	Left	Left deltoid, left triceps				Full recovery	No deficit
4	OPLL	C3-4	58.3	B	After lift of all laminas	Left			Left PT		Full recovery	No deficit
5	OPLL	C6-7	54.6	B	After lift of all laminas	Left	B/L APB, right deltoid, left TA				Full recovery	No deficit
6	OPLL	C3-4	48.1	B	After lift of all laminas	Left	B/L deltoid, TA, AH				Full recovery	No deficit
7	OPLL	C3-4	45.6	B	After lift of all laminas	Left	Left APB				Full recovery	No deficit
8	OPLL	C5-6	45.4	A	After C3 laminectomy	Right	B/L deltoid	Left AH			Partial recovery	No deficit
9	OPLL	C3-4	84.2	A	After C3 laminectomy	Left	Left TA, AH	B/L APB, right TA, right AH		Left median	Full recovery	No deficit
10	OPLL	C3-4	54.5	A	After C3 laminectomy	Left	Right deltoid			Left PT	Full recovery	No deficit
11	OPLL	C4-5	37.1	B	After lift of all laminas	Left		B/L TA, AH			Loss of EP (B/L TA and AH)	Left leg weakness
12	OPLL	C3-4	61.3	A	After C3 laminectomy	Left		Left APB, left AH	Left median		Partial recovery	No deficit
13	CSM	C4-5	38.6	B	After lift of all laminas	Right		B/L APB, right TA, right AH			Full recovery	No deficit

MCL, maximal compressive level; OR, occupying ratio; IONM, intraoperative neurophysiologic monitoring; MEP, motor evoked potential; SSEP, somatosensory evoked potential; OPLL, ossification of the posterior longitudinal ligament; APB, abductor pollicis brevis; TA, tibialis anterior; PT, posterior tibialis; B/L, bilateral; AH, abductor halluces; EP, evoked potential; CSM, cervical spondylotic myelopathy.

Table 1. Literature review of reperfusion injury (white cord syndrome) in cervical surgery

Author	A/G	Diagnosis	Procedure	IONM			Treatment after 1st operation	Post-OP symptoms	Post-OP MRI	Follow up
				Time of change	MEPs	SSEPs				
Chin et al. 2013 [30]	59/M	CSM	C4-5 & C5-6 ACDF	After cage placement at C5-6	Loss	Loss	C5 corpectomy High-dose steroid	C6 tetraplegia	T2-HI with swelling at C5	16 months partial recovery
Zhang et al. 2013 [43]	58/F	CSM	C5 ACCF	N/A			C3-6 laminoplasty High-dose steroid	Tetraplegia	T2-HI with swelling at C5	1 week full recovery
Lee et al. 2014 [9]	49/M	OPLL	C3-4 PCDF	N/A			High-dose steroid	Tetraplegia	T2-HI with swelling at C3-4	12 months partial recovery
	71/M	OPLL	C3-5 PCDF	N/A			PDC at C2 High-dose steroid	Tetraplegia	T2-HI with swelling at C2-C6	3 months partial recovery
Giammalva et al. 2017 [33]	64/M	CSM	C5-6 & C3-4 ACDF	After closing superficial planes	↓	↓	High-dose steroid	Tetraplegia	T2-HI at C5-6	7 days partial recovery
Our case 2017	63/M	CSM	C3-5 PCDF	After lift of lamina	↓	↓	C6 upper laminectomy MAP > 95 mmHg High-dose steroid	Lt. hemiplegia	T2-HI at Lt. C3-4 with swelling	5 months full recovery
Vinodh et al. 2018 [44]	51/F	C3 body tumor	C2-5 PDC C1-2 & C5-6 PCDF	N/A			High-dose steroid	C3 tetraplegia	T2-HI with swelling into the medulla	6 weeks no improvement
Papaioannou et al. 2019 [35]	79/M	CSM	C3-6 PDC C2-7 PCDF	N/A	NC	NC	High-dose steroid	Tetraplegia	T2-HI at C6-7	18 months no improvement
Antwi et al. 2018 [31]	68/M	CSM	C4-7 PDC, C3-7 PCDF	After closing suprafascia	Loss of Lt.	NC	MAP > 113–115 mmHg Replacement of screw High-dose steroid	Lt. hemiplegia	T2-HI at Lt. C5-6	3 days partial recovery
Wiginton et al. 2019 [6]	41/M	CSM	C1-2 PDC	After removal of posterior C1 arch	Loss of UE	Loss	MAP > 95 mmHg C2 upper laminectomy High-dose steroid	Tetraplegia	T2-HI at C1	N/A
Mathkour et al. 2020 [34]	79/M	CSM	C3-5 PDC C2-6 PCDF	After closing fascia	NC	↓	MAP > 85 mmHg High-dose steroid	Worsened Rt. hemiparesis	T2-HI at C2-6	4 moths full recovery
Busack et al. 2020 [36]	63/M	CSM	C3-6 PDC, C2-T1 PCDF	After laminectomy	Loss	↓	MAP > 85 mmHg High-dose steroid	Tetraplegia	N/A	1 month partial recovery
Jun et al. 2020 [45]	49/F	CSR	C6-7 ACDF	N/A			Laminoplasty C4-5-6-7 High-dose steroid	Paraplegia	T2-HI at C6-7	2 weeks full recovery
Liao et al. 2020 [37]	51/M	CSM with OPLL	C3-4 PDC C2-5 PCDF	N/A			High-dose steroid Manitol	Tetraplegia	T2-HI at C4-7	2 months full recovery

C5 palsy

Table 1 Summary of patients which developed C5 nerve root palsy after surgery

Patient	Sex	Age	Diagnosis	Laminectomy	TcMEPs	SSEPs	EMGs	Nerve root palsy	Paresis
1	F	65	Cervical degenerative disc disease	PCF C5-T2/ laminectomy	No change	No change	2	Bilateral C5	Bilateral deltoid
2	F	59	Cervical degenerative disc disease	PCF C2-T1/ laminectomy	No change	No change	2	Right C5	Right deltoid
3	F	63	Cervical degenerative disc disease	C4-7 laminectomy/ foraminotoies	No change	No change	2	Left C5	Left paresis
4	F	61	Cervical degenerative disc disease	C3-7 laminectomy/ fusion	No change	No change	2	None	None
5	F	77	Cervical degenerative disc disease	ACDF C5-T1/PCF C5-T1	No change	No change	2	None	None
6	M	61	Cervical myeloradiculopthy	PCF C3-6/ laminectomy	No change	No change	2	None	None
7	M	70	Cervical degenerative disc disease	PCF C3-T2/ laminectomy	No change	No change	2	None	None
8	M	63	Cervical myeloradiculopathy	PCF C2-T2/ laminectomy	No change	No change	2	None	None
9	M	88	Cervical degenerative disc disease	PCF PCF C3-T1/ laminectomy	No change	No change	2	Bilateral C5	Bilateral deltoid
10	M	73	Cervical myeloradiculopathy	PCF C2-T2/ laminectomy	No change	No change	2	None	None
11	F	44	Cervical myeloradiculopathy	C4-7 Laminoplasty	No change	No change	Not recorded	Bilateral C5	Bilateral deltoid

(Haghighi, Blaskiewicz, Ramirez, & Zhang, 2016)

IONM - Operation

Systemic Factors

Generalization & Gradual pattern

Upper limb controls during thoracic procedures

Technical Factors

Electrodes

Positioning & rechecking impedence

Pathologic Factors

Abrupt focal EP decrement

Mean BP > 80 – 95 mmHg

High dose steroid

Modification of surgical procedure

감 사 합 니 다